FIXED-BASE SIMULATION STUDY OF DECOUPLED LONGITUDINAL
CONTROLS DURING APPROACH AND LANDING OF A MEDIUM JET
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SUMMARY

A fixed-base simulation study has been made to evaluate the use of decoupled longitudinal controls during the approach and landing of a typical twin-engine jet transport in the presence of wind shear. The simulation employed all six rigid-body degrees of freedom. The flight instrumentation included a localizer and a flight director. The primary piloting task was to capture and maintain a 3° glide slope by using the flight director and then to complete the landing by using visual cues provided below an altitude of 200 m by closed-circuit television and a terrain model.

The decoupled longitudinal controls used constant prefilter and feedback gains to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity as commanded through the column, flap lever, and thrust lever, respectively. The decoupled control system demonstrated improved performance over a conventional control system during approaches made in the presence of wind shear although the improvement was not statistically significant for all pilot and wind-shear combinations. The use of the decoupled controls also improved the pilot's ability to complete safe landings. The pilots preferred the decoupled controls and, on a pilot rating scale, rated the approach and landing task 1 to 3 increments better, depending on wind-shear conditions, than when the conventional control system was used.

INTRODUCTION

The approach and landing phases of flight can be quite demanding for transport pilots in the presence of wind shear. Indeed, wind shear has been a significant factor in several airplane crashes (refs. 1 and 2) that occurred during final approach. Studies (refs. 3, 4, and 5) have shown that the use of decoupled controls that provide independent control of flight-path angle, pitch angle, and forward velocity can alleviate the high-workload condition that exists during the landing approach of a simulated short take-off and landing (STOL) transport. In addition, decoupled controls that provide direct control of flight-path angle should be able to respond more rapidly to wind shear than conventional controls which must rotate the airplane in pitch in order to change lift.

The present simulation study compared the performance of decoupled longitudinal controls with conventional controls during the landing approach of a Boeing 737 transport in the presence of wind shear. The decoupled longitudinal control system automatically changed the thrust, elevator position, and symmetric spoilers to produce independent or decoupled control of flight-path angle, pitch angle, and forward velocity. It was believed that most of the benefits of the decoupling concept could be maintained when the system was only approximately decoupled since the pilots would not notice a small amount of coupling. Consequently, no attempt was made to include sensor noise, and the decoupled controller used constant gains which were predetermined from a simple

linear airplane model that did not include complex engine or actuator dynamics. The use of constant gains would avoid the necessity for onboard computation in actual flight but restricted the use of the controller to the approach and landing phases. The airplane states were decoupled only under steady-state conditions, and modern control theory was applied to determine the controls that reach the steady state in an optimal manner.

The fixed-base simulation study employed real-time digital computation of the six-degree-of-freedom nonlinear equations of motion that represent the Boeing 737 airplane. The study used a fixed-base cockpit which included a visual landing display generated through the use of a closed-circuit television and a terrain model board. The simulation included the effects of light, moderate, and severe wind shears and turbulence.

SYMBOLS

A	matrix of aircraft stability coefficients
a_X, a_Z	longitudinal and normal acceleration, respectively, g units (1 g = 9.8 m/sec^2)
B	matrix of aircraft-control coefficients
C	matrix relating desired output vector to state vector
C_m	pitching-moment coefficient
C_W	weight coefficient, $-\dfrac{2mg}{\rho V^2 S}$
C_X	longitudinal-force coefficient
C_Z	normal-force coefficient
$\bar{c}$	mean aerodynamic chord, m
DMR( )	statistical quantity of Duncan multiple range test; parentheses designate particular factor considered
e_i	ith iteration of general variable e
F	calculated test statistic, dimensionless
G	matrix of prefilter gains used in decoupled controller (see appendix A)
g	acceleration due to gravity, m/sec^2
H	matrix of feedback gains used in decoupled controller (see appendix A)

h	altitude, m
I	identity matrix
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, kg-m^2
I_{XZ}	product of inertia, kg-m^2
J	performance index used in determining optimal control (see appendix A)
m	mass of airplane, kg
n	number of flights
P	solution to matrix Riccati equation (see appendix A)
r	angular velocity about Z body axis, deg/sec or rad/sec
Q	state-variable weighting matrix used in performance index J
R	control-variable weighting matrix used in performance index J
R_a	range from aircraft to threshold, measured on Earth's surface, m
$\vec{r}$	vector of commanded inputs by pilot
S	wing area, m^2
s	Laplace operator
T	total thrust, N
t	time, sec
$t(\ )$	statistical quantity of t-test of students' t distribution; parentheses designate particular factor considered
u,w	velocity components along X and Z body axes, respectively, knots
$\vec{u}$	vector of control variables
$\hat{u}$	difference between instantaneous control vector and vector of pilot inputs
V	true airspeed, knots (ft/sec)
X,Y,Z	body axes
$\vec{x}$	vector of state variables

$\vec{x}_e$ vector of state variables at equilibrium conditions

$\hat{x}$ difference between instantaneous and equilibrium state vectors

Y_i inertial axis located at runway threshold, positive Y_i to right

y distance along Y_i-axis, m

$\vec{y}$ vector of state variables to be controlled in a decoupled manner

α angle of attack, deg

β angle of sideslip, deg

γ air-referenced flight-path angle, deg

δ_e elevator deflection, positive for trailing edge down, deg or rad

δ_{sp} spoiler deflection, deg or rad

δ_{th} equivalent throttle deflection

θ pitch angle, deg or rad

μ arithmetic mean, $\dfrac{\sum_{i=1}^{n} e_i}{n}$

ρ air density, kg/m^3

ϕ bank angle, rad or deg

Aircraft stability and control coefficients:

$$C_{X_{\delta_{sp}}} = \frac{\partial C_X}{\partial \delta_{sp}} \qquad C_{Z_{\delta_{sp}}} = \frac{\partial C_Z}{\partial \delta_{sp}} \qquad C_{m_{\delta_{sp}}} = \frac{\partial C_m}{\partial \delta_{sp}}$$

$$C_{X_{\delta_e}} = \frac{\partial C_X}{\partial \delta_e} \qquad C_{Z_{\delta_e}} = \frac{\partial C_Z}{\partial \delta_e} \qquad C_{m_{\delta_e}} = \frac{\partial C_m}{\partial \delta_e}$$

$$C_{X_{\delta_{th}}} = \frac{\partial C_X}{\partial \delta_{th}} \qquad C_{Z_{\delta_{th}}} = \frac{\partial C_Z}{\partial \delta_{th}} \qquad C_{m_{\delta_{th}}} = \frac{\partial C_m}{\partial \delta_{th}}$$

$$C_{X_u} = \frac{\partial C_X}{\partial \frac{u}{V}} \qquad C_{Z_u} = \frac{\partial C_Z}{\partial \frac{u}{V}}$$

$$C_{X_\alpha} = \frac{\partial C_X}{\partial \alpha} \qquad C_{Z_\alpha} = \frac{\partial C_Z}{\partial \alpha} \qquad C_{m_\alpha} = \frac{\partial C_m}{\partial \alpha}$$

$$C_{X_q} = \frac{\partial C_X}{\partial \frac{q\bar{c}}{2V}} \qquad C_{m_q} = \frac{\partial C_m}{\partial \frac{q\bar{c}}{2V}} \qquad C_{Z_q} = \frac{\partial C_Z}{\partial \frac{q\bar{c}}{2V}}$$

$$C_{X_{\dot\alpha}} = \frac{\partial C_X}{\partial \frac{\dot\alpha\bar{c}}{2V}} \qquad C_{m_{\dot\alpha}} = \frac{\partial C_m}{\partial \frac{\dot\alpha\bar{c}}{2V}}$$

Superscripts:

T matrix transpose

-1 matrix inverse

' nondimensional perturbations from equilibrium

Subscripts:

c commanded by pilot

0 trim condition

Abbreviations:

ANOV analysis of variance

DIAS deviation in indicated airspeed from reference condition (130 knots for conventional controls and 122 knots for decoupled controls)

d.o.f. degrees of freedom

ELOC localizer error

GSE glide-slope error

IAS indicated airspeed

IFR instrument flight rules

ILS instrument landing system

rms root mean square

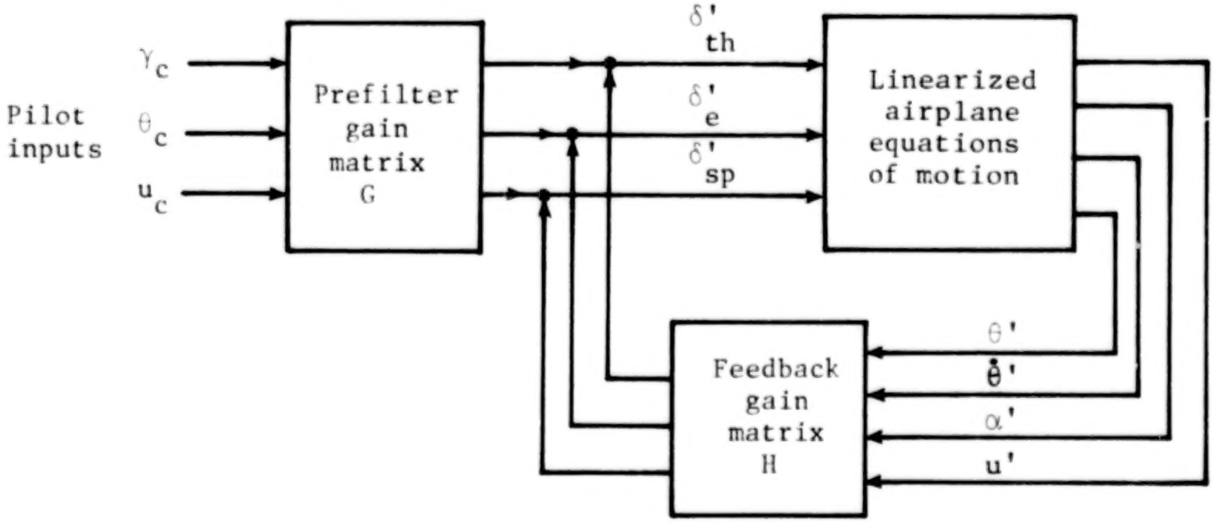
A dot over a symbol denotes differentiation with respect to time.

SIMULATED AIRPLANE DESCRIPTION

The simulated airplane used in this study was a Boeing 737-100 twin-engine medium jet transport. The simulation included detailed response characteristics of the Pratt & Whitney JT8D-7 turbofan engines. The physical characteristics of the simulated airplane are presented in table I, and the initial conditions are given in table II. When flown in the conventional mode, no autothrottle was employed. Longitudinal control was achieved by an elevator and movable stabilizer and directional control by a single-surface rudder. Lateral control was obtained by combined ailerons and spoilers. The wing spoiler arrangement is shown in figure 1. Spoiler panels 2, 3, 6, and 7 were deployed asymmetrically for roll control and symmetrically for longitudinal control when the decoupled controls were used. The ground spoilers could only be employed on the ground to reduce stopping distance.

DECOUPLED CONTROLS

The general approach taken for providing independent or decoupled control of flight-path angle, pitch angle, and forward velocity is depicted in the following sketch:



The decoupled longitudinal controller was mechanized so that the pilot commanded flight-path angle λ_c through inputs to the column, pitch angle θ_c through the flap lever, and forward velocity u_c through the throttle. In addition, the thumb controller on the left horn of the control yoke was used to trim flight-path angle (at a constant 1°/sec rate) so that the pilot would not be required to hold the column forward during descent. The decoupled controller required that the airplane pitch angle, pitch rate, angle of attack, and forward velocity be continuously measured.

The feedback gain matrix H and prefilter gain matrix G result in the aircraft control elements (throttle δ_T', elevator δ_e', and symmetric spoilers δ_{sp}') moving to produce steady-state decoupled control of flight-path angle, pitch angle, and forward velocity as commanded by the pilot. The most versatile means for obtaining G and H would be the use of an onboard computer to find the time-varying adaptive gains. However, the simplified approach used in reference 3 was also used in the present investigation where the use of the controller was restricted to the approach and landing phase of operations. Consequently, constant prefilter and feedback gains (calculated for the conditions in table II) could be used so that onboard computation would not be necessary when the system was used on an actual airplane. The decoupled longitudinal control law is developed in appendix A.

SIMULATION EQUIPMENT

The digital-computer program used in the present simulation employed nonlinear equations of motion for six rigid-body degrees of freedom and an iteration rate of 32 per second. The data, which are airframe-manufacturer proprietary, include engine and actuator dynamics and a nonlinear aerodynamic representation of the airplane up to the region of stall. The transport-type cockpit (fig. 2) was flown from the left seat and was equipped with conventional flight and engine-thrust control devices. The simulator control forces were representative of current medium jet-transport aiplanes and were provided by a hydraulic servosystem as functions of control displacement and rate. The flight-instrument display was also representative of current transport airplanes consisting of an electromechanical attitude-direction indicator including glide-slope error, a vertical-speed indicator, a horizontal-situation indicator, an altimeter, an airspeed indicator, meters for angles of attack and sideslip, and a turn and bank indicator. The flight director is described in detail in reference 6. No display of flight-path angle was included in the flight-instrument display, and the pilots were instructed to use the instrumentation as they would in normal operations whether conventional controls or decoupled controls were used.

The visual cues for flare and landing were obtained by means of a 675-scan-line color television camera that moved over a terrain model (fig. 3) in response to the six-degree-of-freedom nonlinear equations of motion representing the airplane. The visual display was presented to the pilot through a television monitor and collimating lens system mounted in the pilot's windshield.

The wind-hazard data used in this study were produced for the Federal Aviation Administration (FAA) by Stanford Research Institute as one of the tasks in their Wind Hazard Definition Study and are briefly described in reference 7. Each wind profile is composed of three-axis mean wind specifications and Dryden turbulence specifications. All specifications are modeled in the simulator by means of a table lookup given as a function of both altitude and range from the runway threshold. Six wind-shear profiles (denoted B2, B3, B6, B7, D3, and D10) were chosen from reference 7 to be used in the present simulation study. Profiles B2 and B3 (figs. 4 and 5) were representative of low-intensity wind shears and had little turbulence. (See table III.) Profiles B6 and B7 (figs. 6 and 7) were representative of moderate wind shears. In addition, B7 included turbulence (table IV) with vertical rms gust intensities up to 8 knots. Two very severe wind shears (figs. 8 and 9) which also include the turbulence shown in table IV were also simulated. These two shears are denoted D3 and D10, and the latter is a reconstruction of the wind shear that was present at the Eastern Airlines crash at the John F. Kennedy International Airport in 1975.

TEST PROGRAM

Three research pilots were required to perform six flights in each wind condition (light, moderate, and severe) with each control system. Each research pilot was qualified to fly the B-737 airplane, and the combinations of wind shear and control configuration were randomized (ref. 8) through the use of a latin square. The pilot's task was to assume command of the airplane in level flight and use the flight-director command bars and glide-slope-error indicator to capture and maintain the localizer and glide slope under IFR conditions. The flights were initiated at an altitude of 457 m, with the airplane initially below the glide slope. When the decoupled control system was used, the pitch attitude was nominally set at 3° to keep the nose wheel off the ground at touchdown. The commanded speed was set at 122 knots (the desired touchdown speed) shortly after flight initiation by moving the throttle lever to a reference mark. The decoupled control system then attempted to maintain the commanded pitch attitude and speed as the flight progressed without further pilot attention. When the airplane intercepted the ILS beam, the pilots trimmed the airplane onto the desired 3° descent path by using the trim button on the control yoke. Depressing the trim button caused the commanded flight-path angle to change at a constant rate (1°/sec) and, with practice, permitted fairly accurate attainment of the 3° descent path. The pilots then used the column to make any changes in flight-path angle that became necessary due to wind conditions. The pilots used only conventional instrumentation during this study even though they believed that their performance would have been enhanced if a display of commanded flight-path angle had been included. At an altitude of 61 m, the pilot was to visually acquire the runway and land nominally 305 m down the runway from threshold. When conventional B-737 controls were used, the pilots normally attempted to maintain the initial 130-knot airspeed until just before touchdown. The decoupled control system is compared with the conventional control system on a statistical basis during the landing approach. The touchdown performance is measured against standards presented in reference 9. Pilot ratings are also used to compare the control systems.

RESULTS AND DISCUSSION

Typical time histories illustrating the use of decoupled controls and conventional controls under the influence of light and severe wind shears are presented for reference in figures 10 to 13. The time history of a typical flight using decoupled controls in light wind shear B3 is presented in figure 10 with pilot C at the controls. The control characteristics of the decoupled system can be seen during the first part of this flight. Eight seconds into the flight, the pilot commanded a speed reduction to approximately 125 knots. The control system performed the required speed reduction, with no resulting change in pitch angle and only a small change in flight-path angle. Several small commanded changes in flight-path angle were made beginning at 2 sec as the pilot attempted to capture the glide slope. The response of the system to commanded flight-path-angle changes can, however, be better seen from the more isolated input, approximately 48 sec into the run. The commanded flight-path-angle change was accomplished with almost no change in pitch attitude and approximately a 1-knot reduction in airspeed. The pilot tracked the glide slope (GSE in fig. 10) very closely until just before landing some 550 m down the runway with a sink rate of 0.90 m/sec. The time history of a typical flight using conventional controls in wind shear B3 is presented in figure 11. In this light wind shear, there was little difference between the performance with the two control systems. The only parameter that differed very much was indicated airspeed IAS, which the pilot allowed to reach 145 knots before reducing thrust when conventional controls were used. The pilot was able to perform a satisfactory approach and landed 229 m down from the threshold.

Although successful approaches could generally be made with the conventional controls in light-shear conditions, severe shear such as D10 precluded success, as shown in figure 12. During this flight with the conventional control system, pilot C failed to recognize the sharp speed reduction that occurred at an altitude of approximately 50 m until it was too late. The pilot pitched the nose up and increased thrust, but the airplane impacted 204 m short of the runway. It should be noted that pilots would normally not attempt landings in wind conditions given by condition D10. However, when they attempted landings in this study, they generally impacted short of the runway when conventional controls were used. When landings were attempted in the same wind conditions with the decoupled control system, the pilots were generally able to attain the runway, as shown in figure 13. On this flight, the decoupled control system kept the speed from falling below 112 knots and the airplane landed 165 m down from the threshold with a sink rate of 1.75 m/sec. The decoupled control system also maintained constant pitch attitude during the approach (fig. 13), even in severe wind shear. The spoilers and thrust occasionally reached their limits during approaches in severe wind shear. However, the subjects did not notice any difference in performance.

Approach Performance

The performance data for the approach phase of the study (fig. 14) consisted of rms values (from data taken every 0.03125 sec during the last 200 m

of altitude) of flight-path angle, glide-slope error, deviation in indicated airspeed, localizer error, and the control inputs to the wheel and column. The deviation in indicated airspeed was measured relative to the 130-knot trim condition when conventional controls were used and relative to the commanded 122-knot reference speed when decoupled controls were used. The symbols shown in figure 14 generally denote the mean values of the six flights performed by each pilot, with each control system, under each wind condition. It should be noted that the means were not always based upon six flights when conventional controls were used because there were several flights with high sink rates at impact in which data were lost because the model protection system automatically put the computer in "reset" before the rms data were processed. The extreme case was when pilot A used the conventional controls in severe wind shear and lost data due to high sink rates on five out of six flights. With this exception, the mean values of the flight-path angle, the glide-slope error, and the deviation in indicated airspeed were improved for all pilots at all wind conditions when decoupled controls were used. The improvement due to the use of decoupled controls was not statistically significant at the 95-percent level for all pilot and wind-shear combinations. A statistical analysis is presented in appendix B which examines the various pilot, control, and wind interactions in detail.

The localizer error showed no consistent effects due to the type of control system used, nor did the control column activity. However, the control-wheel activity did show that there was more activity when the decoupled control system was used. The pilots did not report this increase in activity but did state that the decoupled control system reduced the workload for the longitudinal task to the point that the lateral mode became dominant. Thus, the pilots probably spent more effort controlling the lateral mode when decoupled controls were used for the longitudinal mode.

The performance with the two control systems is graphically demonstrated by the approach profiles for pilot B in figures 15, 16, and 17 for light, moderate, and severe wind shears, respectively. The approach profiles are presented in terms of altitude versus time from touchdown and appear steeper than would be the case if presented in terms of altitude versus range. In light and moderate shears, the decoupled control system exhibited very consistent performance whereas the conventional control system resulted in some large altitude excursions. In severe wind shears, the decoupled control was not capable of the degree of consistency shown in the lesser shears. However, pilot B was able to land the airplane with decoupled controls but impacted short of the runway on four out of six runs with conventional controls. Although the severe wind shears were so extreme that landings would not normally be attempted, the pilots did so during the simulation, and the touchdown performance is included.

Touchdown Performance

The dominant fact associated with the touchdown performance was that the pilots often failed to reach the runway when conventional controls were used. (See fig. 18.) The pilots impacted short of the runway with high sink rates

almost 50 percent of the time (24 times in 54 attempts) with conventional controls. As previously mentioned, 11 of the runs that impacted with high sink rates resulted in lost data because the model protection system automatically put the computer in reset before the data were printed out. By comparison, the pilots landed short of the runway only once (fig. 18(c)) when decoupled controls were used, and that was by 16 m with a 1.8 m/sec sink rate.

The mean touchdown performance is summarized in figure 19. The touchdown performance parameters examined during this investigation were longitudinal and lateral position; pitch angle and bank angle; and sink rate, forward velocity, and lateral velocity. Lateral velocity was not presented because of a problem with the data at touchdown for that parameter. The limits shown in figure 19 reflect Category II requirements discussed in reference 9. The mean values of all six performance parameters were generally well within these limits for all pilots under all wind conditions when decoupled controls were used.

The conventional control system did not yield such consistent results. All three pilots had at least one touchdown parameter that was outside the limits when conventional controls were used in severe winds. The mean range of pilots A and B at touchdown was short of the runway (fig. 19) when conventional controls were used in severe wind shear. Although pilot C landed on the runway an average of 170 m down from threshold with conventional controls, he generally landed hard, with a mean sink rate of 3.2 m/sec in severe winds. In addition, pilot C landed on the nose wheel at a mean pitch altitude of -3° in severe winds with conventional controls. Although the major differences between the two control systems occurred under severe wind conditions, there are statistically significant differences at the 95-percent confidence level in light and moderate winds, as discussed in appendix C.

Pilot Opinion

In responding to a questionnaire, pilots B and C stated that the decoupled control system improved control during the approach in all levels of wind shear and also improved performance during flare and touchdown. They believed that the pilot workload was relieved and rated the task with the decoupled control system at a pilot rating (table V) of 1 to 3 increments better, depending on the wind conditions, than when conventional controls were used. Of the 3-increment improvement in severe wind shear, pilot C stated that 1 point of improvement was due to the autothrottle aspects of the decoupled controls and 2 points were due to decoupling itself. Typical pilot ratings with conventional controls in light wind shear were 4 to 5, and in severe wind shear they were 7 to 9. Pilot A stated that he liked the decoupled control system but did not return the pilot questionnaire. All three pilots believed that their performance with decoupled controls was hampered by the lack of a display of commanded flight-path angle. The pilots stated that the severe shears and turbulence were much more severe than anything they had experienced operationally but that the results would not be appreciably altered if a less severe representation had been used.

Supplementary Investigation

Effect of sensor errors.- The results of this investigation were obtained assuming that there were no sensor errors in the measurements of the state variables (i.e., θ, $\dot{\theta}$, α, and u) required for feedback control and that the stability and control coefficients were known perfectly. Reference 10 has shown that the effects on the decoupling process of relatively large errors in these quantities are generally minor in nature. In order to demonstrate this characteristic, pilot A performed 14 landings, 7 with perfect sensors, and 7 with a 20-percent error in the measurement of each state variable. In each case, three runs were performed in light wind shear, two in moderate wind shear, and two in severe wind shear. The pilot could not detect the effect of the sensor errors, and none of the approach parameters or touchdown parameters were significantly different statistically. Of all the parameters, the deviation in indicated airspeed during approach came closest to showing a statistically significant difference, with an F value of 1.44 compared with a critical F value of 4.75 for a 5-percent significance (95-percent confidence) level.

Stall avoidance.- When the spoilers are set at 9° with 40° flaps, the stall speed was computed to be approximately 2.5 knots greater than that of the normal B-737 landing configuration. In addition, the decoupled control system was set to maintain the airplane at a pitch attitude of 3° throughout the approach and landing. As a result, the angle of attack was 6° in still air (fig. 10) during a 3° approach using the decoupled control system, and the angle of attack was 3° or less (fig. 11) with conventional controls. It would appear that the decoupled control system might be more prone to stalling in severe wind-shear conditions than the conventional control system. Consequently, the maximum angle of attack experienced during each of the 54 runs made with decoupled controls was examined relative to that experienced during 54 runs made with conventional controls. (See table VI.) The analysis of variance indicated that there was no statistically significant difference in maximum angle of attack between decoupled and conventional controls. However, the decoupled control system actually reduced the maximum angle of attack during severe wind shears. The average maximum angle of attack exceeded 15.5° (buffet onset) for two of the three pilots in severe winds when conventional controls were used, but was less than 12.5° for all three pilots when decoupled controls were used. (See table VI.) As previously noted, the pilots impacted short of the runway several times when conventional controls were used. In severe wind shear, the loss of control when conventional controls were used was generally the result of stalling the aircraft.

CONCLUDING REMARKS

A fixed-base simulation study has been conducted to evaluate the use of decoupled longitudinal controls as a means for improving pilot performance during approach and landing of a typical twin-engine jet transport (Boeing 737) in the presence of wind shear. The resulting decoupled control system employed the throttle, the elevators, and the symmetric spoilers as active control elements to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity. Restricting the controller to the approach and landing phase of operations permitted the use of constant prefilter and feedback gains

in the decoupled control mechanization and, in an actual airplane application, would avoid the need for onboard computation. The piloting task was to use a conventional localizer and flight director to capture and maintain a 3° glide slope until breakout at 61-m altitude in the presence of wind shear, and land 305 m from the threshold by using a visual landing display generated by closed-circuit television.

Results from this study indicated the following:

1. The use of the decoupled longitudinal control system improved performance during landing approaches over a range of wind-shear conditions. Longitudinal approach parameters that showed an improvement included flight-path angle, glide-slope error, and deviation in indicated airspeed. There was considerable variability of performance between pilots at the different wind conditions. The improvement due to the use of the decoupled control system was not statistically significant for all pilot and wind combinations.

2. The use of decoupled controls enabled the pilots to successfully complete landings in the presence of severe wind shear. Only one flight out of 54 attempts touched down short of the runway when decoupled controls were used, although almost 50 percent of the attempts made with conventional controls were short of the runway. In addition, the use of decoupled controls improved the average sink rate, forward velocity, and pitch attitude at touchdown. However, there was considerable variability in touchdown performance between pilots at the different wind conditions.

3. The pilots stated that the decoupled control system improved performance and reduced workload in the longitudinal control mode in all wind-shear conditions, and they rated the task 1 to 3 increments better on a pilot-rating scale, depending on wind conditions, than when conventional controls were used.

4. The introduction of 20-percent error in the measurement of pitch angle, pitch rate, angle of attack, and forward velocity required for feedback control was not detected by the pilot and had no effect on approach or landing performance.

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APPENDIX A

DECOUPLED LONGITUDINAL CONTROLS

The three longitudinal equations of motion were linearized as perturbations about an equilibrium condition in equation (1-59) of reference 11. These three equations can be nondimensionalized with respect to time using

$$t' = \frac{V_0}{\bar{c}} t \tag{A1}$$

and, neglecting $C_{Z_{\dot{\alpha}}}$ and C_{Z_q}, solved simultaneously to give

$$\begin{aligned}\frac{d^2\theta'}{dt'^2} = \frac{1}{2\mu K_Y^2}\Bigg[&\left(\frac{C_{m_q} + C_{m_{\dot{\alpha}}}}{2}\right)\frac{d\theta'}{dt'} + \left(C_{m_\alpha} + \frac{C_{m_{\dot{\alpha}}} C_{Z_\alpha}}{4\mu}\right)\alpha' \\ &+ \left(C_{m_u} + \frac{C_{m_{\dot{\alpha}}} C_{Z_u}}{4\mu}\right)u' + \left(C_{m_{\delta_{th}}} + \frac{C_{m_{\dot{\alpha}}} C_{Z_{\delta_{th}}}}{4\mu}\right)\delta'_{th} \\ &+ \left(C_{m_{\delta_e}} + \frac{C_{m_{\dot{\alpha}}} C_{Z_{\delta_e}}}{4\mu}\right)\delta'_e + \left(C_{m_{\delta_{sp}}} + \frac{C_{m_{\dot{\alpha}}} C_{Z_{\delta_{sp}}}}{4\mu}\right)\delta'_{sp}\Bigg]\end{aligned} \tag{A2}$$

$$\frac{d\alpha'}{dt'} = \frac{1}{2\mu}\left(2\mu\frac{d\theta'}{dt'} + C_{Z_\alpha}\alpha' + C_{Z_u}u' + C_{Z_{\delta_{th}}}\delta'_{th} + C_{Z_{\delta_e}}\delta'_e + C_{Z_{\delta_{sp}}}\delta'_{sp}\right) \tag{A3}$$

$$\begin{aligned}\frac{du'}{dt'} = \frac{1}{2\mu}\Bigg[&C_W\theta' + \left(\frac{C_{X_q} + C_{X_{\dot{\alpha}}}}{2}\right)\frac{d\theta'}{dt'} + \left(C_{X_\alpha} + \frac{C_{X_{\dot{\alpha}}} C_{Z_\alpha}}{4\mu}\right)\alpha' + \left(C_{X_u} + \frac{C_{X_{\dot{\alpha}}} C_{Z_u}}{4\mu}\right)u' \\ &+ \left(C_{X_{\delta_{th}}} + \frac{C_{X_{\dot{\alpha}}} C_{Z_{\delta_{th}}}}{4\mu}\right)\delta'_{th} + \left(C_{X_{\delta_e}} + \frac{C_{X_{\dot{\alpha}}} C_{Z_{\delta_e}}}{4\mu}\right)\delta'_e \\ &+ \left(C_{X_{\delta_{sp}}} + \frac{C_{X_{\dot{\alpha}}} C_{Z_{\delta_{sp}}}}{4\mu}\right)\delta_{sp}\Bigg]\end{aligned} \tag{A4}$$

APPENDIX A

The terms $C_{Z_{\dot{\alpha}}}$ and C_{Z_q} given in reference 11 were neglected. Also, $\sin \Theta$ was assumed to equal 0 and $\cos \Theta$ to equal 1 (Θ is the angle between the horizon and X equilibrium axis).

The primed parameters are perturbations from the equilibrium or trim conditions of the airplane in nondimensional form; that is,

$$\theta' = \theta - \theta_0 \tag{A5}$$

$$\alpha' = \alpha - \alpha_0 = \frac{w - w_0}{u_0} \tag{A6}$$

$$u' = \frac{u - u_0}{u_0} \tag{A7}$$

and where

$$\mu = \frac{m}{\rho S \bar{c}} \tag{A8}$$

$$K_Y{}^2 = \frac{I_Y}{m\bar{c}^2} \tag{A9}$$

The mass and dimensional characteristics of the simulated airplane are presented in tables I and II. Constant coefficients were employed in the linearized longitudinal equations of motion corresponding to an angle of attack of 4°, a forward velocity of 125 knots, and a thrust coefficient of 0.1735.

The linearized longitudinal equations of motion can be written in state vector notation as

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \tag{A10}$$

where the state vector is

$$\vec{x} = \begin{bmatrix} \theta' \\ \dot{\theta}' \\ \alpha' \\ u' \end{bmatrix} \tag{A11}$$

and the control vector is

$$\vec{u} = \begin{bmatrix} \delta'_{th} \\ \delta'_e \\ \delta'_{sp} \end{bmatrix} \tag{A12}$$

The general control law is given as

$$\vec{u} = -H\vec{x} + G\vec{r} \tag{A13}$$

where $\vec{r}$ is the vector of commanded pilot inputs γ_c, u_c, and θ_c that are to be controlled in a decoupled manner. The output equation is

$$\vec{y} = C\vec{x} \tag{A14}$$

When equation (A13) is substituted into equation (A10), the Laplace transform of the result can be written as

$$\vec{x}(s) = (sI - A + BH)^{-1}BG\vec{r}(s) \tag{A15}$$

Substituting the Laplace transform of equation (A14) into equation (A15) and requiring that the output $\vec{y}(s)$ be equal to the commanded pilot input $\vec{r}(s)$ under steady-state conditions results in the prefilter gain

$$G = -\left[C(A - BH)^{-1}B\right]^{-1} \tag{A16}$$

Having obtained the prefilter gain matrix G required for decoupled steady-state control, it is desirable to obtain the control that will reach that condition as efficiently as possible. Consequently, modern control theory was employed to obtain the feedback gain matrix H.

For a given constant-pilot input $\vec{r}$, there is an associated equilibrium state $\vec{x_e}$ that is reached in the steady-state case; that is,

$$0 = (A - BH)\vec{x_e} + BG\vec{r} \tag{A17}$$

which, since it is zero, can be subtracted from the closed-loop equations of motion,

$$\dot{\hat{x}} = (A - BH)\vec{x} + BG\vec{r} - \left[(A - BH)\vec{x_e} + BG\vec{r}\right] \tag{A18}$$

where $\hat{x}$ is the difference between the instantaneous state $\vec{x}$ and the new equilibrium state $\vec{x_e}$. Equation (A18) is, therefore,

$$\dot{\hat{x}} = (A - BH)\hat{x} \tag{A19}$$

which can be written as

$$\dot{\hat{x}} = A\hat{x} + B\hat{u} \tag{A20}$$

where

$$\hat{u} = -H\hat{x} \tag{A21}$$

which is the difference between the instantaneous control vector $\vec{u}$ and the pilot-control input associated with the new equilibrium state. The performance index

$$J = \int_0^\infty \left(\hat{x}^T Q\hat{x} + \hat{u}^T R\hat{u}\right) dt \tag{A22}$$

and equation (A20) constitute the familiar state-regulator problem with quadric performance index for which the optimal control $\hat{u}^*$ (ref. 12) is

$$\hat{u}^* = -R^{-1}B^T P\hat{x} \tag{A23}$$

where P is the solution to the time invariant matrix Riccati equation

$$PA + A^T P - PBR^{-1}B^T P + Q = 0 \tag{A24}$$

The particular solution for the Riccati equation is based on the iterative approach taken in reference 13.

Equating the general control $\hat{u}$ to the optimal control $\hat{u}^*$ permits the solution for the remaining unknown gain matrix

$$H = R^{-1}B^TP \tag{A25}$$

The feedback gain H is optimal for a given set of weighting matrices Q and R in the performance index (eq. (A22)). The off-diagonal terms in these weighting matrices were zero, whereas the diagonal terms were varied as a function of pilot opinion early in the simulation. The final values which were used in this study were

$$Q = \begin{bmatrix} 1.0 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 \\ 0 & 0 & 0.02 & 0 \\ 0 & 0 & 0 & 0.5 \end{bmatrix} \tag{A26}$$

and

$$R = \begin{bmatrix} 0.005 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.01 & 0 \\ 0 & 0 & 0 & 0.01 \end{bmatrix} \tag{A27}$$

The resulting prefilter and feedback gain matrices were

$$G = \begin{bmatrix} 3.9304 & 9.6802 & 8.0530 \\ -0.8772 & 1.5967 & -1.8829 \\ -8.0800 & 3.8552 & 11.6078 \end{bmatrix} \tag{A28}$$

and

$$H = \begin{bmatrix} 1.1336 & 16.9936 & 0.606 & 5.4089 \\ -3.1518 & -31.1558 & 0.6122 & 0.6983 \\ 3.3400 & 42.7517 & 0.8662 & -0.6189 \end{bmatrix} \quad \text{(A29)}$$

These matrices were converted to the appropriate dimensions and implemented through the general control law $\bar{u} = -H\vec{x} + G\vec{r}$ using the six-degree-of-freedom nonlinear equations simulating the B-737.

APPENDIX B

STATISTICAL ANALYSIS OF APPROACH PERFORMANCE

An anaysis of variance ANOV (refs. 8 and 14) was performed on each approach performance parameter to determine whether any of the experimental factors (pilots, wind shears, or control systems) or their interactions were statistically significant at the 95-percent confidence (5-percent significance) level or greater. That is, the analysis was to determine whether the probability of two sample means being from different populations when they were actually from the same population was less than 5 percent. The ANOV (table VII) showed that the type of control was statistically significant at the 99-percent confidence level for flight-path angle, glide-slope error, deviation in indicated airspeed, and wheel activity. Wind conditions were a statistically significant factor at the 95-percent confidence level or greater for all the approach parameters. The effect of pilots was statistically significant at the 95-percent confidence level for the control wheel and column inputs and also for glide-slope error. The interaction effects between pilots and controls were statistically significant at the 95-percent confidence level or greater for glide-slope error and wheel activity. In addition, the winds interacted with the controls at the 99-percent confidence level for flight-path angle and deviation in indicated airspeed.

In this experiment, there were two or more levels for each experimental factor. The two levels of the controls were conventional controls and decoupled controls; the three pilot levels were pilots A, B, and C; and the three wind levels were light, moderate, and severe. Because the ANOV showed each factor to be statistically significant, further testing was necessary to determine at which levels of each factor the means were significantly different. It should be noted that the standard error used in testing the pilot and wind levels included only that data associated with the particular control system being considered rather than data pooled for both control systems. The results of level testing are presented in tables VIII and IX, along with the mean and standard deviation, for conventional controls and decoupled controls, respectively. When the t-test was applied to winds, the light shear condition was the reference against which the other winds were tested, as is indicated in tables VIII and IX. In a like manner, conventional controls were chosen as the reference (table VIII) when the t-test was applied to controls.

The Duncan multiple range (DMR) test was performed to determine which pilot's performance differed significantly from the others. For example, δ_{column} with conventional controls (table VIII) had a significant pilot effect. In the case of light wind shears, the DMR test indicated (table VIII) that the difference between the performance of pilots A and B was not statistically significant nor was the difference between pilots B and C. However, the difference between the performance of pilots A and C was statistically significant at the 95-percent confidence level. The six approach performance parameters are discussed in the following paragraphs.

APPENDIX B

Flight-Path Angle

Decoupled controls produced closer adherence to the desired 3° flight-path angle for all pilots and all wind conditions than conventional controls. (Compare tables VIII and IX.) The improvement was statistically significant (table IX) for five out of nine pilot and wind combinations. As indicated by the ANOV (table VII), the effect of pilots was not statistically significant. Flight-path-angle performance degraded as wind severity increased. However, the degradation was statistically significant only for severe wind shears with either conventional (table VIII) or decoupled (table IX) controls.

Glide-Slope Error

Glide-slope error was reduced when decoupled controls were used for all pilot/wind combinations except pilot A in severe winds, for which five or six runs were lost due to the model protection device when conventional controls were used. The reduction was statistically significant at or above the 95-percent confidence level (table IX) for five out of nine possible pilot/wind combinations. The degradation due to wind shear was generally statistically significant only for severe winds. As indicated by the DMR test, the pilot effects were statistically significant (table IX) only under severe wind conditions when decoupled controls were used when pilot A made larger errors than either pilot B or C.

Deviation in Indicated Airspeed

The deviation in indicated airspeed (DIAS) was measured relative to the 130-knot trim speed when conventional controls were used and relative to the commanded 122-knot reference airspeed when decoupled controls were used. The deviation in indicated airspeed was less with decoupled controls for all pilots and all wind shears than was the case with conventional controls. The improvement was statistically significant at the 95-percent confidence level for four out of nine pilot and wind combinations. (See table IX.) The wind effect was, in general, statistically significant only when the winds were severe. Pilot effects were not statistically significant.

Localizer Error

The localizer error was essentially statistically unaffected by pilots, winds, or controls. There was a wind-shear effect, but it was statistically significant only when pilot B used decoupled controls in severe wind shear.

Column Inputs

The effect of the type of control on column inputs was not statistically significant. There was a pilot effect, but it was only statistically significant when conventional controls were used (table VIII) when pilot C made smaller inputs than pilot A in light winds and smaller inputs than pilot B in

moderate winds. The wind effects were statistically significant but only when the winds became severe. (See tables VIII and IX.)

Wheel Inputs

The decoupled control system was not directly associated with lateral control mode. However, the pilots generally made larger wheel inputs when decoupled controls were used than when conventional controls were used. All three factors, pilots, winds, and controls, were statistically significant. However, the pilot effect was only statistically significant (table IX) at one point (i.e., when pilot A made smaller inputs than pilot B when decoupled controls were used in severe winds). The control effects (table IX) were not statistically significant in severe shears. Larger control inputs were made as the winds increased. The increased activity was generally statistically significant in severe winds for both control systems. (See tables VIII and IX.)

STATISTICAL ANALYSIS OF TOUCHDOWN PERFORMANCE

An analysis of variance ANOV (refs. 8 and 14) was performed on each performance parameter to determine whether any of the experimental factors (pilots, wind shears, or control systems or their interactions) were statistically significant at the 95-percent confidence (5-percent significance) level or greater. The ANOV (table X) showed that, of the longitudinal parameters, only range from threshold R_a and sink rate $\dot{h}$ had no statistically significant pilot effects. Wind-shear effects were statistically significant for forward velocity, pitch angle, and range from threshold. The ANOV also shows that the type of control was statistically significant for sink rate, forward velocity, and pitch angle. The control effect was not the same for all pilots, with the pilot/control interactions (table X) being statistically significant at the 95-percent confidence level for forward velocity and pitch angle. The control/wind interaction effects were also statistically significant for sink rate, pitch angle, and range from threshold. Consequently, further testing was performed to determine for which pilots and wind conditions the effect of the control system was statistically significant. The results are presented, along with the mean and standard deviation, in tables XI and XII for conventional controls and decoupled controls, respectively. As previously mentioned in appendix B, the light wind shear was the reference against which the other winds were tested when the t-tests were performed. (See tables XI and XII.) Also, conventional controls were the reference (table XI) when the t-tests were applied to controls. The Duncan multiple range (DMR) test was performed to determine which pilot's performance differed significantly from the others. The six touchdown parameters are discussed in the following paragraphs.

Sink Rate

The improvement due to the use of decoupled controls was statistically significant for two of three pilots in both light and severe wind shear (table XII) but was not statistically significant in moderate wind shear. Winds and pilots were not statistically significant factors (table X) for sink rate.

Forward Velocity

The effect of controls on forward velocity was statistically significant for four out of nine pilot/wind combinations. Winds were statistically significant but only when conventional controls were used (table XI) in severe winds. Pilot effects were only statistically significant when conventional controls were used in moderate shears and then only because pilot C landed at higher speeds than either pilot A or B.

Pitch Attitude

The effect of the type of controls on pitch attitude was statistically significant (table XII) for six out of nine pilot/wind combinations. The degradation in pitch attitude as a function of wind was statistically significant when conventional controls were used (table XI) for pilots A and C in both moderate and severe winds. The effect of winds had no statistically significant effect on pitch attitude when decoupled controls were used. Pilot effects were statistically significant for both conventional and decoupled controls.

Range From Threshold

The effect of the type of controls and the pilots on range from threshold R_a was not statistically significant (table X), and the effect of winds was statistically significant only when conventional controls were used. (See tables XI and XII.)

Lateral Displacement and Bank Angle

Pilots, winds, and controls were generally statistically significant factors for lateral displacement and bank angle. (See tables X, XI, and XII.)

REFERENCES

1. Aircraft Accident Report - Iberia Lineas Aereas De Espana (Iberian Airlines); McDonnell Douglas DC-10-30, EC CBN-Logan International Airport, Boston, Massachusetts; December 17, 1973. NTSB-AAR-74-14, Nov. 8, 1974.

2. Aircraft Accident Report - Eastern Air Lines, Inc.; Boeing 727-225; John F. Kennedy International Airport, Jamaica, New York; June 24, 1975. NTSB-AAR-76-8, Mar. 12, 1976.

3. Miller, G. Kimball, Jr.; Deal, Perry L.; and Champine, Robert A.: Fixed-Base Simulation Study of Decoupled Controls During Approach and Landing of a STOL Transport Airplane. NASA TN D-7363, 1974.

4. Miller, G. Kimball, Jr.; and Deal, Perry L.: Moving-Base Visual Simulation Study of Decoupled Controls During Approach and Landing of a STOL Transport Aircraft. NASA TN D-7790, 1975.

5. Feinreich, Benjamin; Seckel, Edward; and Ellis, David R.: In-Flight Simulation Study of Decoupled Longitudinal Controls for the Approach and Landing of a STOL Aircraft. NASA CR-2710, 1977.

6. Parrish, Russell V.; and Martin, Dennis J., Jr.: Comparison of a Linear and a Nonlinear Washout for Motion Simulators Utilizing Objective and Subjective Data From CTOL Transport Landing Approaches. NASA TN D-8157, 1976.

7. Dieudonne, James E.: Comments on a Proposed Standard Wind Hazard Environment and Its Use in Real-Time Aircraft Simulations. AIAA Paper 79-0324, Jan. 1979.

8. Dixon, Wilfrid J.; and Massey, Frank J., Jr.: Introduction to Statistical Analysis. McGraw-Hill Book Co., c.1969.

9. Johnson, Walter A.; and Hoh, Roger H.: Determination of ILS Category II Decision Height Window Requirements. NASA CR-2024, 1972.

10. Hamer, Harold A.; and Johnson, Katherine G.: Effects of Errors on Decoupled Control Systems. NASA TP-1184, 1978.

11. Blakelock, John H.: Automatic Control of Aircraft and Missiles. John Wiley & Sons, Inc., c.1965.

12. Athans, Michael; and Falb, Peter L.: Optimal Control. McGraw-Hill Book, Co., Inc., c.1966.

13. Kleinman, David L.: On an Iterative Technique for Riccati Equation Computations. IEEE Trans. Automat. Contr., vol. AC-13, no. 1, Feb. 1968, pp. 114-115.

14. Adler, Henry L.; and Roessler, Edward B.: Introduction to Probability and Statistics. W. H. Freeman and Co., c.1972.

TABLE I.- B-737 AIRPLANE DIMENSION AND DESIGN DATA

General:	
Overall length, m	28.65
Height to top of vertical fin, m	11.28
Wing:	
Area, m^2	91.04
Span, m	28.35
Mean aerodynamic chord, m	3.41
Incidence angle, deg	1
Aspect ratio	8.83
Taper ratio	0.279
Dihedral, deg	6
Sweep (quarter-chord), deg	25
Flap deflection (maximum), deg	40
Aileron deflection (maximum), deg	±20
Spoilers deflection (maximum):	
Inboard ground spoilers (maximum), deg	60
All other spoilers (maximum), deg	40
Horizontal tail:	
Total area, m^2	28.99
Span, m	10.97
Stabilizer deflection (maximum), deg	-14, +3
Elevator deflection (maximum), deg	±21
Vertical tail:	
Total area, m^2	20.8
Rudder deflection, deg	±24
Weight:	
Maximum take-off gross weight, kN	431
Design landing weight, kN	399
Operational empty weight, kN	297
Propulsion system (two Pratt & Whitney JT8D-7 engines):	
Maximum uninstalled thrust per engine at sea level static, kN	62.3
Effective engine moment arms about center of gravity:	
Lateral arm, m	4.94
Vertical arm, m	1.52

TABLE II.- INITIAL CONDITIONS FOR SIMULATION

Weight, kN	408
Moments of inertia:	
I_X, kg-m^2	602 000
I_Y, kg-m^2	1 090 000
I_Z, kg-m^2	1 780 000
I_{XZ}, kg-m^2	71 600
Center of gravity, percent of mean aerodynamic chord	30
Altitude, m	457
Field elevation, m	2
Indicated airspeed, knots	130
Flight-path angle, deg	0
Trailing-edge flap position, deg	40
Flight spoiler initial position (decoupled controls), deg	9
Landing-gear position	Down

TABLE III. TURBULENCE SPECIFICATIONS FOR LIGHT WIND SHEARS

(a) Wind shear B2

Altitude, m	Longitudinal rms, knots	Lateral rms, knots	Vertical rms, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	0.65	0.65	0.09	32.22	15.15	3.17
22.86	1.63	1.63	.15	55.47	32.89	12.10
45.72	3.61	3.61	.25	79.74	53.00	24.23
91.44	4.76	4.76	.31	112.78	84.28	48.46
137.16	.50	.50	.09	139.57	111.59	72.69
182.88	.25	.25	.06	161.82	135.82	96.93
228.60	.00	.00	.00	161.82	135.82	96.93
457.20	.00	.00	.00	161.82	135.82	96.93

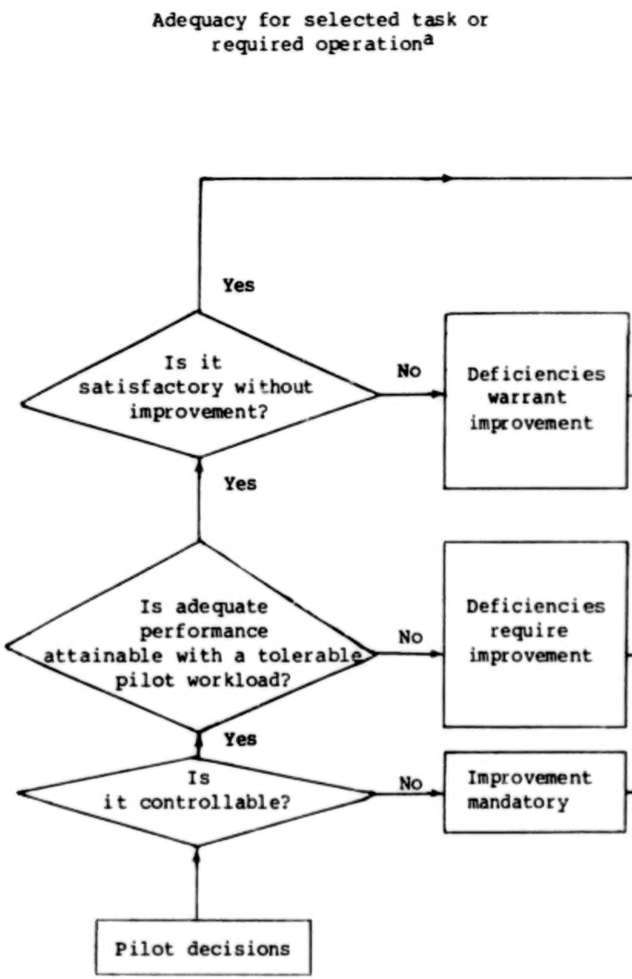
(b) Wind shear B3

Altitude, m	Longitudinal rms, knots	Lateral rms, knots	Vertical rms, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	0.65	0.65	0.09	79.49	79.49	1.52
22.86	1.63	1.63	.15	674.85	674.85	5.72
45.72	3.61	3.61	.25	2383.31	2383.31	11.43
91.44	4.76	4.76	.31	5389.73	5389.73	22.86
137.16	.50	.50	.09	1058.33	1058.33	34.29
182.88	.25	.25	.06	793.75	793.75	45.72
228.60	.00	.00	.00	793.75	793.75	45.72
457.20	.00	.00	.00	793.75	793.75	45.72

TABLE IV.- TURBULENCE SPECIFICATIONS FOR WIND SHEARS B7, D3, AND D10

Altitude, m	Longitudinal rms, knots	Lateral rms, knots	Vertical rms, knots	Longitudinal scale length, m	Lateral scale length, m	Vertical scale length, m
6.10	3.40	2.70	2.34	32.23	15.15	3.17
30.49	4.05	3.46	3.53	66.07	40.91	16.16
60.98	4.43	3.95	4.35	93.45	65.09	32.32
121.95	4.85	4.50	5.36	132.16	103.54	64.63
182.93	5.11	4.86	6.05	161.86	135.85	96.95
457.32	5.74	5.78	7.94	256.37	251.37	242.47

TABLE V.- PILOT RATING SYSTEM



Control characteristics	Demands on the pilot in selected task or required operation[a]	Pilot rating
Excellent, highly desirable	Pilot compensation not a factor for desired performance	1
Good, negligible deficiencies	Pilot compensation not a factor for desired performance	2
Fair, some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation; controllability not in question	7
Major deficiencies	Considerable pilot compensation is required for control	8
Major deficiencies	Intense pilot compensation is required to retain control	9
Major deficiencies	Control will be lost during some portion of required operation	10

[a]Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

TABLE VI.- COMPARISON OF MAXIMUM ANGLE OF ATTACK DURING APPROACH USING DECOUPLED AND CONVENTIONAL CONTROLS

(a) Conventional control data

Statistical parameter	Light shears			Moderate shears			Severe shears		
	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
Mean	7.6	6.7	5.6	8.7	8.9	7.0	16.8	16.7	13.8
Standard deviation	1.9	.8	1.8	1.2	3.9	3.7	3.7	3.2	1.9

(b) Decoupled control data

Statistical parameter	Light shears			Moderate shears			Severe shears		
	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
Mean	6.6	7.6	7.4	8.8	9.2	9.5	11.5	12.3	12.3
Standard deviation	.7	.7	.5	2.8	2.0	2.9	1.1	1.1	1.9

(c) Analysis of variance

Statistical parameter	Pilot	Wind	Control	Pilot/control	Control/wind	Pilot/wind	Pilot/wind/control	Error
d.o.f.	2	2	1	2	2	4	4	90
F	1.87	[a]100.81	3.28	[b]4.34	[a]12.79	.15	.55	---
F_{05}	3.10	3.10	3.95	3.10	3.10	2.47	2.47	---
F_{01}	4.85	4.85	6.93	4.85	4.85	3.53	3.53	---

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE VII.- ANALYSIS OF VARIANCE FOR RMS APPROACH PARAMETERS (FROM 200-m ALTITUDE POINT)

WITH PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

Experimental factors	γ		GSE		ELOC		DIAS		δ_{wheel}		δ_{column}	
	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F
Pilot	2	2.73	2	[a]3.79	2	2.36	[illegible]	1.29	2	[a]4.49	2	[a]3.14
Wind	2	[b]14.41	2	[b]14.95	2	[a]6.26	2	[b]7.17	2	[b]16.41	2	[b]16.38
Control	1	[b]48.04	1	[b]15.60	1	0.27	1	[b]26.28	1	[b]16.69	1	.71
Pilot/control interaction	2	2.40	2	[a]5.88	2	1.12	2	0.17	2	[b]5.03	2	.42
Control/wind interaction	2	[b]10.14	2	2.99	2	1.62	2	[b]5.84	2	.69	2	2.67
Pilot/wind interaction	4	.49	4	[a]2.54	4	.83	4	1.14	4	1.07	4	.48
Pilot/control/wind interaction	4	2.40	4	2.07	4	.37	4	.35	4	.52	4	.42
Error[c]	79	-----	79	-----	79	----	79	-----	79	-----	79	-----

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.96, 3.11, and 2.48 for 1, 2, and 4 degrees of freedom, respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 7.01, 4.92, and 3.60 for 1, 2, and 4 degrees of freedom, respectively).

[c]Data for 11 runs with conventional controls were lost due to model protection device to reduce d.o.f. by 11.

TABLE VIII.- RMS APPROACH DATA (FROM 200-m ALTITUDE) FOR CONVENTIONAL CONTROLS

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
γ, deg	Mean	3.721	3.791	3.514	3.641	3.981	3.457	4.283	5.408	4.368
	Standard deviation	0.329	0.535	0.613	0.791	0.462	0.440	0	1.020	0.849
	t (controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t (winds)	Reference	Reference	Reference	0.21	0.66	0.18	1.39	[a]2.76	1.69
	DMR (pilots)	Not statistically significant (ANOV)								
GSE, m	Mean	9.88	8.06	7.09	11.62	10.89	13.68	10.01	13.86	19.35
	Standard deviation	2.48	2.79	2.53	5.60	4.09	8.88	0	1.01	5.18
	t (controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t (winds)	Reference	Reference	Reference	0.63	1.40	1.75	0.04	[a]3.09	[b]4.63
	DMR (pilots)	(A-B), (B-C), (A-C)			(C-A), (A-B), (C-B)			(C-B), (B-A), (C-A)		
ELOC, m	Mean	33.75	17.13	14.92	35.26	23.91	16.14	14.74	24.42	31.05
	Standard deviation	24.65	6.88	10.52	18.53	8.94	10.40	0	3.90	23.31
	t (controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t (winds)	Reference	Reference	Reference	0.11	1.47	0.06	0.63	1.50	1.38
	DMR (pilots)	Not statistically significant (ANOV)								

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE VIII.- Concluded

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
DIAS, knots	Mean	7.35	7.19	5.96	8.10	8.40	9.84	13.34	10.76	16.94
	Standard deviation	1.11	2.06	1.69	2.45	3.16	7.12	0	2.24	12.28
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	0.63	0.79	1.31	[b]4.42	2.11	[b]14.06
	DMR(pilots)	Not statistically significant (ANOV)								
δ_{wheel}, deg	Mean	8.909	7.117	7.829	9.865	9.225	8.294	8.594	13.029	14.629
	Standard deviation	1.713	1.230	5.213	2.753	1.732	2.397	0	2.284	2.041
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	0.66	[a]2.42	0.20	0.15	[b]4.48	[a]2.48
	DMR(pilots)	(A-C), (C-B), (A-B)			(A-B), (B-C), (A-C)			(C-B), (B-A), (C-A)		
δ_{column}, deg	Mean	1.572	1.415	1.066	1.633	1.724	1.178	2.173	2.606	1.922
	Standard deviation	0.263	0.360	0.205	10.927	0.432	10.384	0	0.565	0.288
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	0.11	1.34	0.62	1.86	[a]3.38	[b]5.17
	DMR(pilots)	(A-B), (B-C), [a](A-C)			(B-A), (A-C), [a](B-C)			(B-A), (A-C), (B-C)		

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE IX.- RMS APPROACH DATA (FROM 200-m ALTITUDE) FOR DECOUPLED CONTROLS

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
γ, deg	Mean	3.004	3.060	3.047	3.245	3.195	3.195	3.660	3.580	3.394
	Standard deviation	0.139	0.101	0.058	0.362	0.321	0.284	0.480	0.234	0.191
	t(controls)	[b]4.38	[b]3.29	[c]1.86	0.99	[b]3.42	0.39	0.97	[b]3.68	[a]2.47
	t(winds)	Reference	Reference	Reference	1.17	0.96	1.23	[b]3.18	[b]3.71	[a]2.89
	DMR(pilots)	Not statistically significant (ANOV)								
GSE, m	Mean	3.96	4.93	3.10	10.20	4.58	6.59	19.98	6.55	7.35
	Standard deviation	0.61	2.77	1.23	7.08	2.04	2.81	11.88	3.47	2.43
	t(controls)	[b]5.11	1.95	[b]3.48	0.33	[b]3.38	1.87	0.63	[a]3.15	[b]4.56
	t(winds)	Reference	Reference	Reference	1.35	0.22	[a]2.68	[b]3.47	0.99	[b]3.26
	DMR(pilots)	(B-A), (A-C), (B-C)			(A-C), (C-B), (A-B)			[b](A-C), (C-B), [b](A-B)		
ELOC, m	Mean	18.21	17.17	13.32	34.78	26.61	21.07	44.89	39.04	24.47
	Standard deviation	12.30	7.06	7.46	19.34	11.27	9.85	38.99	25.29	17.08
	t(controls)	Not statistically significant (ANOV)								
	t(winds)	Reference	Reference	Reference	1.10	0.99	1.10	1.77	[a]2.30	1.59
	DMR(pilots)	Not statistically significant (ANOV)								

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Data fails homogeneity of variance test at the 1-percent level which masks the difference between means.

TABLE IX.- Concluded

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
DIAS, knots	Mean	4.86	3.18	3.82	5.27	5.01	5.43	5.66	5.89	6.74
	Standard deviation	2.45	0.85	0.93	2.28	1.51	2.62	2.01	0.90	1.81
	t (controls)	1.90	[b]4.30	[a]2.48	1.79	2.17	1.30	[a]3.23	[a]3.25	[c]1.65
	t (winds)	Reference	Reference	Reference	0.30	[a]2.58	1.41	0.62	[b]7.27	[b]3.52
	DMR (pilots)	Not statistically significant (ANOV)								
δ_{wheel}, deg	Mean	6.706	10.878	10.623	11.487	17.805	13.213	11.322	19.036	16.347
	Standard deviation	2.028	3.713	7.463	3.518	6.085	2.107	1.806	6.729	7.999
	t (controls)	1.74	[a]2.39	0.75	0.76	[b]3.32	[b]3.78	1.13	0.35	0.42
	t (winds)	Reference	Reference	Reference	[b]3.23	2.12	0.70	[a]3.12	[a]2.50	1.54
	DMR (pilots)	(B-C), (C-A), (B-A)			(B-C), (C-A), (B-A)			(B-A), (A-C), [a](B-C)		
δ_{column}, deg	Mean	0.627	0.910	0.611	1.407	1.848	1.363	1.886	2.513	1.886
	Standard deviation	0.273	0.518	0.150	1.118	0.832	0.809	0.873	1.703	0.942
	t (controls)	Not statistically significant (ANOV)								
	t (winds)	Reference	Reference	Reference	1.63	1.42	1.79	[a]2.62	[a]2.43	[a]3.04
	DMR (pilots)	(B-A), (A-C), (B-C)			(B-A), (A-C), (B-C)			(B-A), (A-C), (B-C)		

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.
[c]Data fails homogeneity of variance test at the 1-percent level which masks the difference between means.

TABLE X.- ANALYSIS OF VARIANCE FOR TOUCHDOWN PARAMETERS WITH PILOTS, CONTROLS, AND WINDS AS EXPERIMENTAL FACTORS

Experimental factors	R_a		y		$\dot{h}$		u		θ		ϕ	
	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F	d.o.f.	F
Pilot	2	0.75	2	[a]3.99	2	1.00	2	[a]4.53	2	[b]22.65	2	0.56
Wind	2	[a]4.12	2	.45	2	1.15	2	[a]3.62	2	[a]4.55	2	1.77
Control	1	3.03	1	2.55	1	[b]44.18	1	[a]4.44	1	[b]32.55	1	.30
Pilot/control interacton	2	.63	2	1.14	2	.13	2	[b]11.82	2	[b]12.55	2	.38
Control/wind interaction	2	[b]9.25	2	.88	2	[b]6.68	2	2.38	2	[a]4.30	2	.57
Pilot/wind interaction	4	.48	4	.13	4	.98	4	.13	4	[b]3.95	4	1.60
Pilot/control/wind interaction	4	1.57	4	1.59	4	.12	4	.49	4	[b]8.70	4	1.01
Error[c]	79	-----	79	-----	79	-----	79	-----	79	------	79	----

[a]Statistical significance at the 5-percent level ($F_{critical}$ = 3.96, 3.11, and 2.48 for 1, 2, and 4 degrees of freedom, respectively).

[b]Statistical significance at the 1-percent level ($F_{critical}$ = 7.01, 4.92, and 3.60 for 1, 2, and 4 degrees of freedom, respectively).

[c]Data for 11 runs with conventional controls were lost due to model protection device to reduce d.o.f. by 11.

TABLE XI.- TOUCHDOWN DATA FOR CONVENTIONAL CONTROLS

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
$\dot{h}$, m/sec	Mean	1.86	1.89	2.35	1.95	2.29	1.89	3.63	2.44	3.17
	Standard deviation	0.73	0.82	1.19	0.58	0.64	0.70	0	1.34	1.65
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Not statistically significant (ANOV)								
	DMR(pilots)	Not statistically significant (ANOV)								
R_a, m	Mean	15.2	115.2	86.8	436.8	272.5	477.1	-291.5	-107.4	167.0
	Standard deviation	51.5	132.3	140.9	280.7	279.6	367.3	0	210.9	446.6
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	[a]3.30	1.25	[a]2.43	[b]5.51	1.70	0.38
	DMR(pilots)	Not statistically significant (ANOV)								
u, knots	Mean	114.5	117.2	125.5	120.1	119.5	130.4	107.0	119.3	132.4
	Standard deviation	1.2	5.0	11.0	6.2	5.9	5.1	0	14.0	16.3
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	2.24	0.73	0.99	[b]5.79	0.29	0.75
	DMR(pilots)	(C-B), (B-A), (C-A)			[a](C-A), (A-B), [b](C-B)			(C-B), (B-A), (C-A)		

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE XI.- Concluded

Experimental factors	Statistical parameters	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
θ, deg	Mean	3.2	3.3	1.7	1.3	1.9	-0.8	9.2	5.2	-3.1
	Standard deviation	0.6	1.0	1.5	0.5	1.8	1.7	0	6.9	1.4
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Reference	Reference	Reference	[b]6.33	1.63	[a]2.71	[b]9.27	0.58	[b]8.40
	DMR(pilots)	(B-A), (A-C), (B-C)			(B-A), [a](A-C), [a](B-C)			(A-B), (B-C), [b](A-C)		
y, m	Mean	-4.1	2.0	0.4	-0.2	2.2	-4.9	-6.5	4.1	-4.2
	Standard deviation	5.9	6.6	4.0	2.9	6.3	12.6	0	3.9	18.4
	t(controls)	Not statistically significant (ANOV)								
	t(winds)	Not statistically significant (ANOV)								
	DMR(pilots)	(A-B), (B-C), (A-C)			(C-B), (B-A), (C-A)			(A-C), (C-B), (A-B)		
ϕ, deg	Mean	1.6	-0.2	0.3	0.4	1.1	1.7	2.9	1.7	1.9
	Standard deviation	2.4	2.7	1.0	3.6	4.0	2.1	0	3.5	5.2
	t(controls)	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference	Reference
	t(winds)	Not statistically significant (ANOV)								
	DMR(pilots)	Not statistically significant (ANOV)								

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE XII.- TOUCHDOWN DATA FOR DECOUPLED CONTROLS

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
$\dot{h}$, m/sec	Mean	1.10	1.01	1.01	1.34	1.80	1.46	1.13	1.13	1.10
	Standard deviation	0.24	0.37	0.49	0.58	0.85	0.46	0.30	0.37	0.61
	t (controls)	2.17	[a]2.42	[a]2.59	1.57	1.12	1.28	[b]6.89	1.97	[a]2.58
	t (winds)	Not statistically significant (ANOV)								
	DMR (pilots)	Not statistically significant (ANOV)								
R_a, m	Mean	356.4	275.4	240.6	233.9	251.3	234.2	279.8	216.2	302.9
	Standard deviation	153.2	63.4	73.4	145.7	217.2	192.7	47.2	95.6	247.2
	t (controls)	Not statistically significant (ANOV)								
	t (winds)	Reference	Reference	Reference	1.70	0.29	0.06	1.06	0.72	0.58
	DMR (pilots)	Not statistically significant (ANOV)								
u, knots	Mean	127.6	125.6	124.0	121.8	122.9	121.4	129.2	127.0	126.5
	Standard deviation	2.8	1.6	4.5	7.7	4.8	6.1	1.8	5.0	3.2
	t (controls)	[b]8.81	[b]3.93	0.31	0.36	1.09	[a]1.79	[b]10.42	1.06	0.78
	t (winds)	Reference	Reference	Reference	2.08	1.14	0.96	0.57	0.59	0.92
	DMR (pilots)	(A-B), (B-C), (A-C)			(B-A), (A-C), (B-C)			(A-B), (B-C), (A-C)		

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

TABLE XII.- Concluded

Experimental factors	Statistical parameter	Light shears			Moderate shears			Severe shears		
		Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C	Pilot A	Pilot B	Pilot C
θ, deg	Mean	3.2	3.8	3.1	3.1	3.6	3.0	3.0	3.5	2.9
	Standard deviation	0.0	0.0	0.2	0.5	0.4	0.3	0.2	0.3	0.4
	t(controls)	0.00	1.19	[a]2.33	[b]5.37	[a]2.24	[b]5.39	[b]4.29	0.53	[b]9.34
	t(winds)	Reference	Reference	Reference	0.56	1.25	0.71	1.22	1.88	1.12
	DMR(pilots)	[b](B-A), (A-C), [b](B-C)			[a](B-A), (A-C), [a](B-C)			[b](B-A), (A-C), [b](B-C)		
y, m	Mean	3.8	1.0	-6.7	2.8	5.4	0.6	3.2	1.3	1.5
	Standard deviation	3.3	4.1	2.3	6.4	3.8	8.8	4.1	5.0	4.0
	t(controls)	Not statistically significant (ANOV)								
	t(winds)	Not statistically significant (ANOV)								
	DMR(pilots)	(C-A), (A-B), [a](C-B)			(B-A), (A-C), (B-C)			(A-C), (C-B), (A-B)		
ϕ, deg	Mean	0.2	1.0	0.1	0.2	-2.5	1.4	1.0	4.4	2.2
	Standard deviation	1.0	3.4	2.6	3.9	4.3	1.6	1.5	7.7	1.5
	t(controls)	Not statistically significant (ANOV)								
	t(winds)	Not statistically significant (ANOV)								
	DMR(pilots)	Not statistically significant (ANOV)								

[a]Statistical significance at the 5-percent level.
[b]Statistical significance at the 1-percent level.

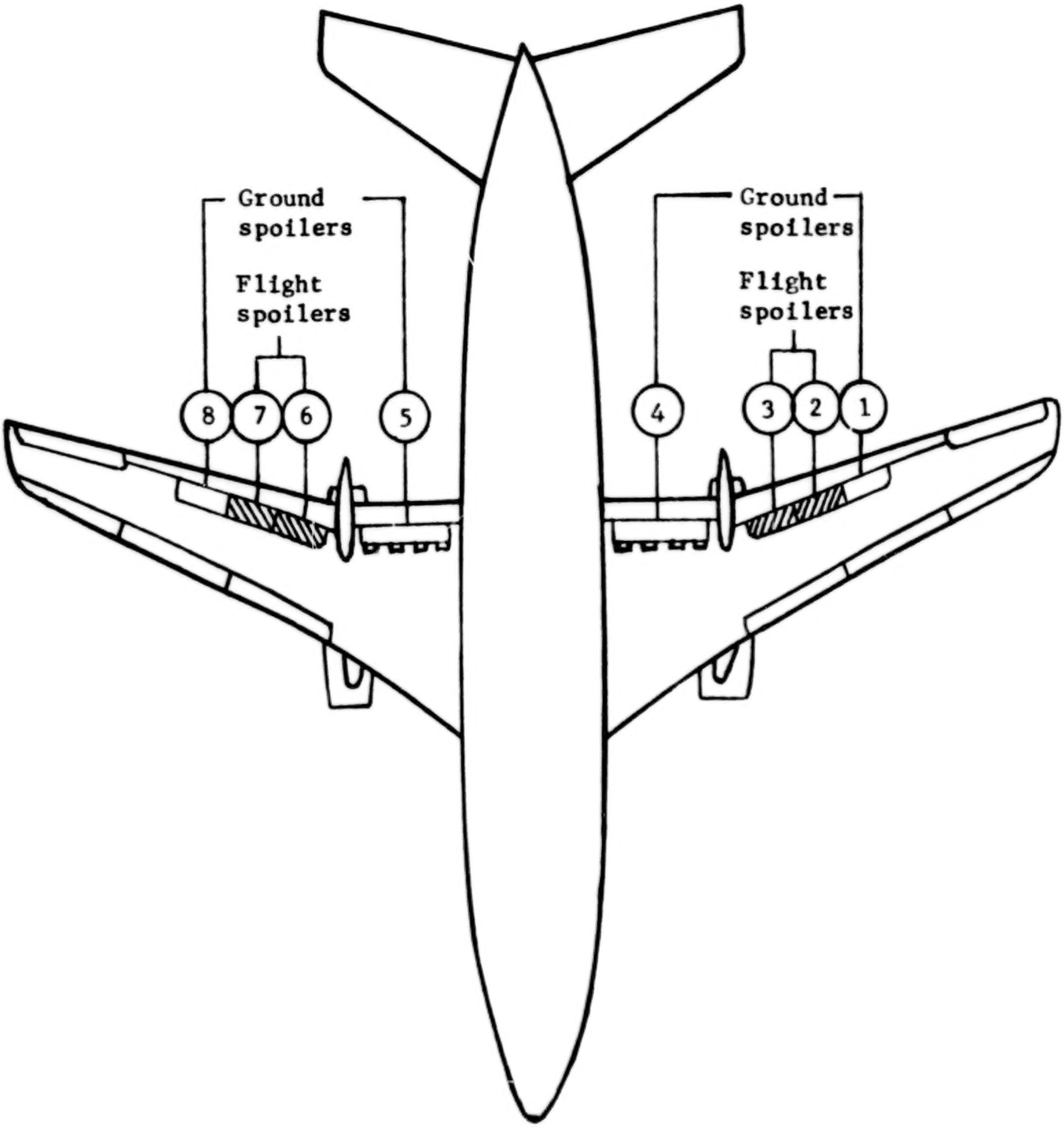


Figure 1.- Spoiler panel identification.

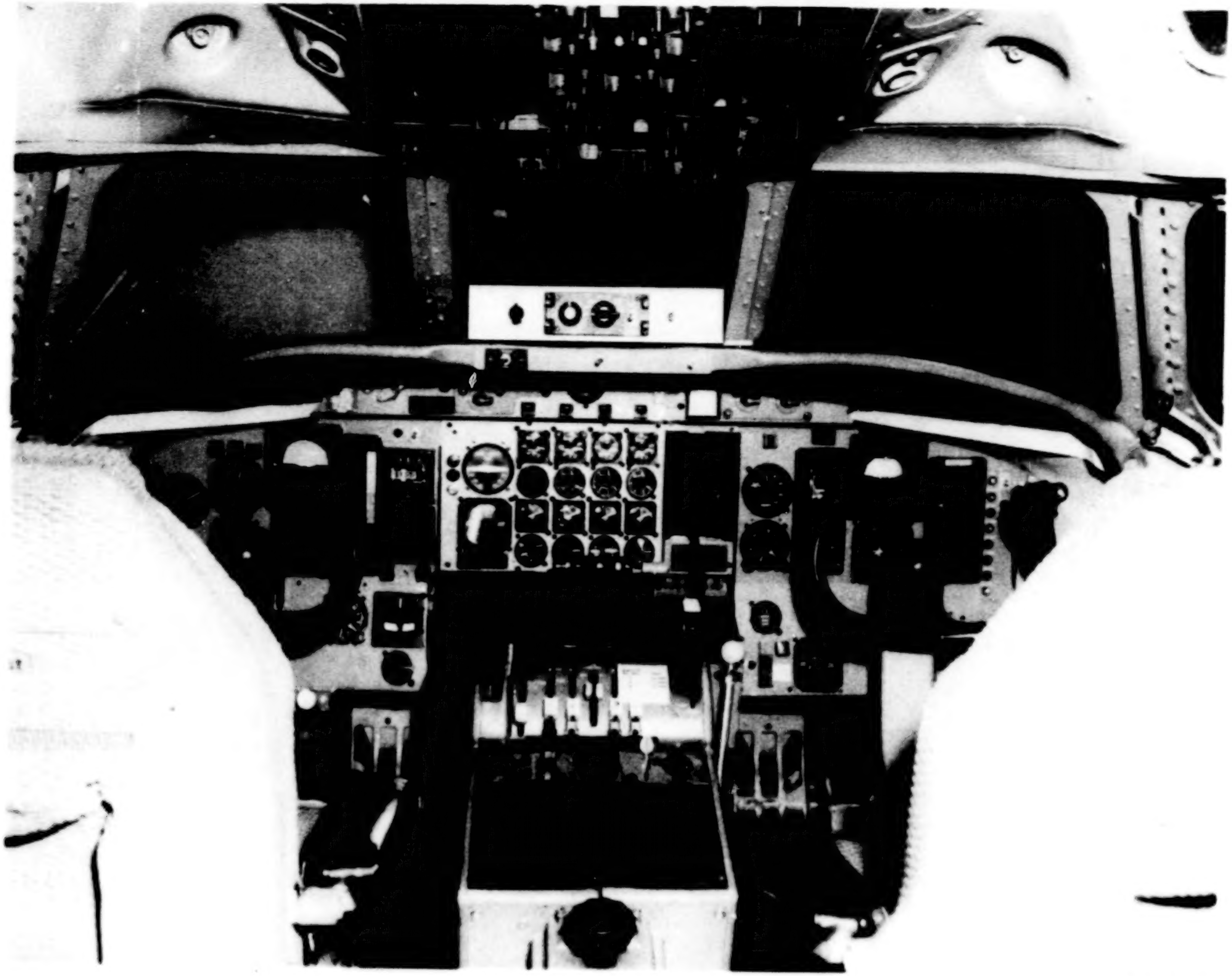


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Figure 2.- Simulator cockpit.

L-76-4924

Figure 3.- Airport model.

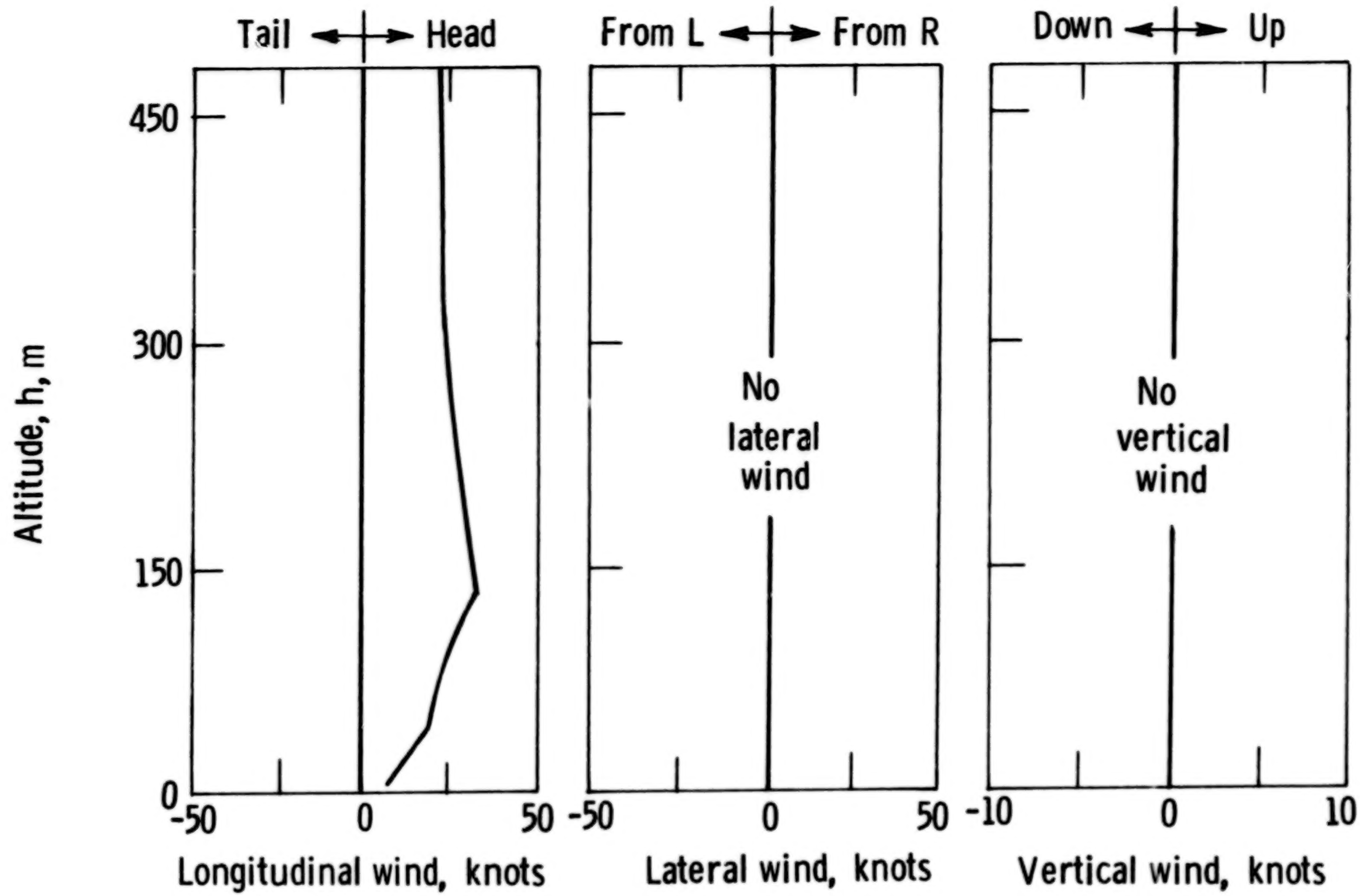

Figure 4.- Wind profile B2 (low severity).

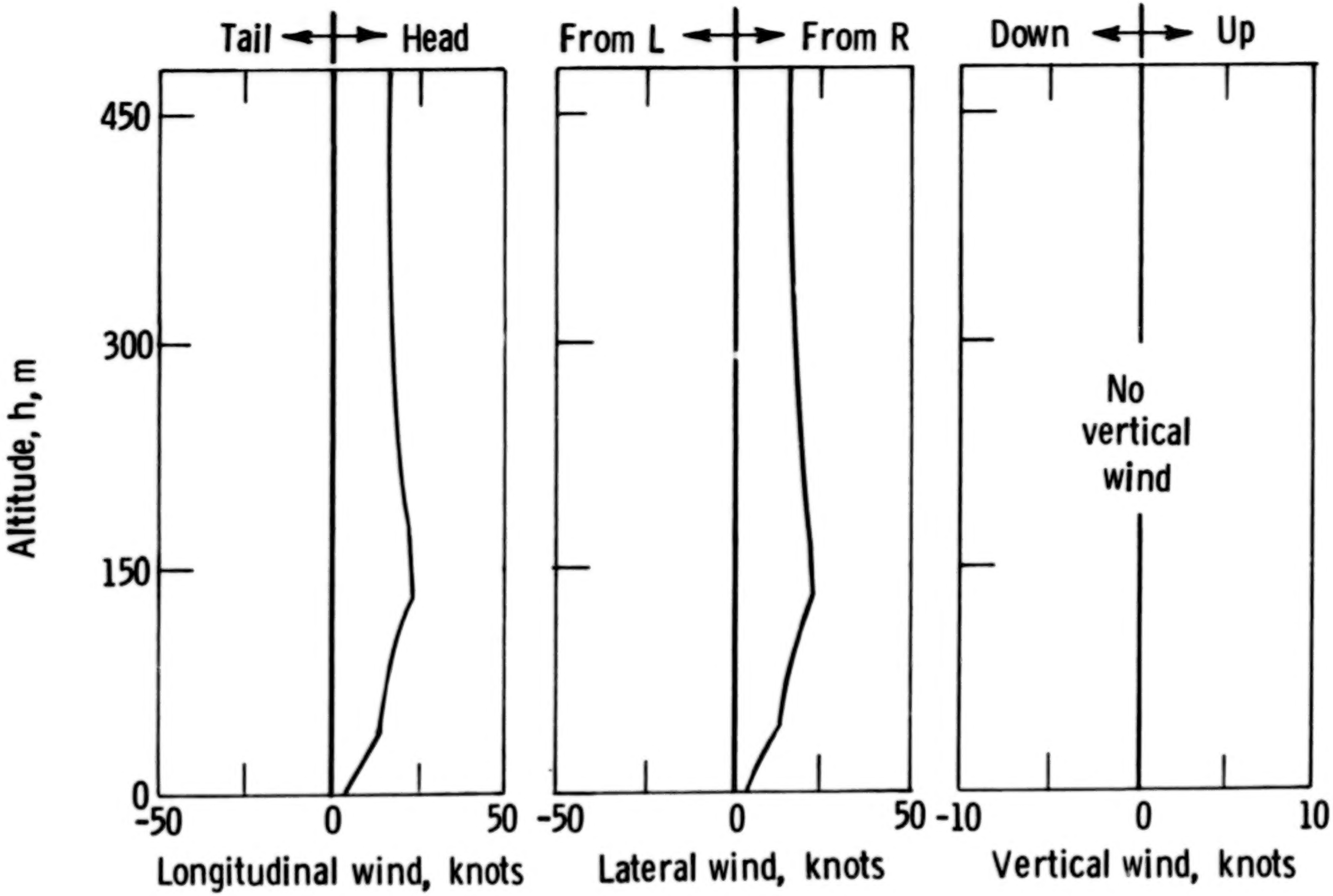

Figure 5.- Wind profile B3 (low severity).

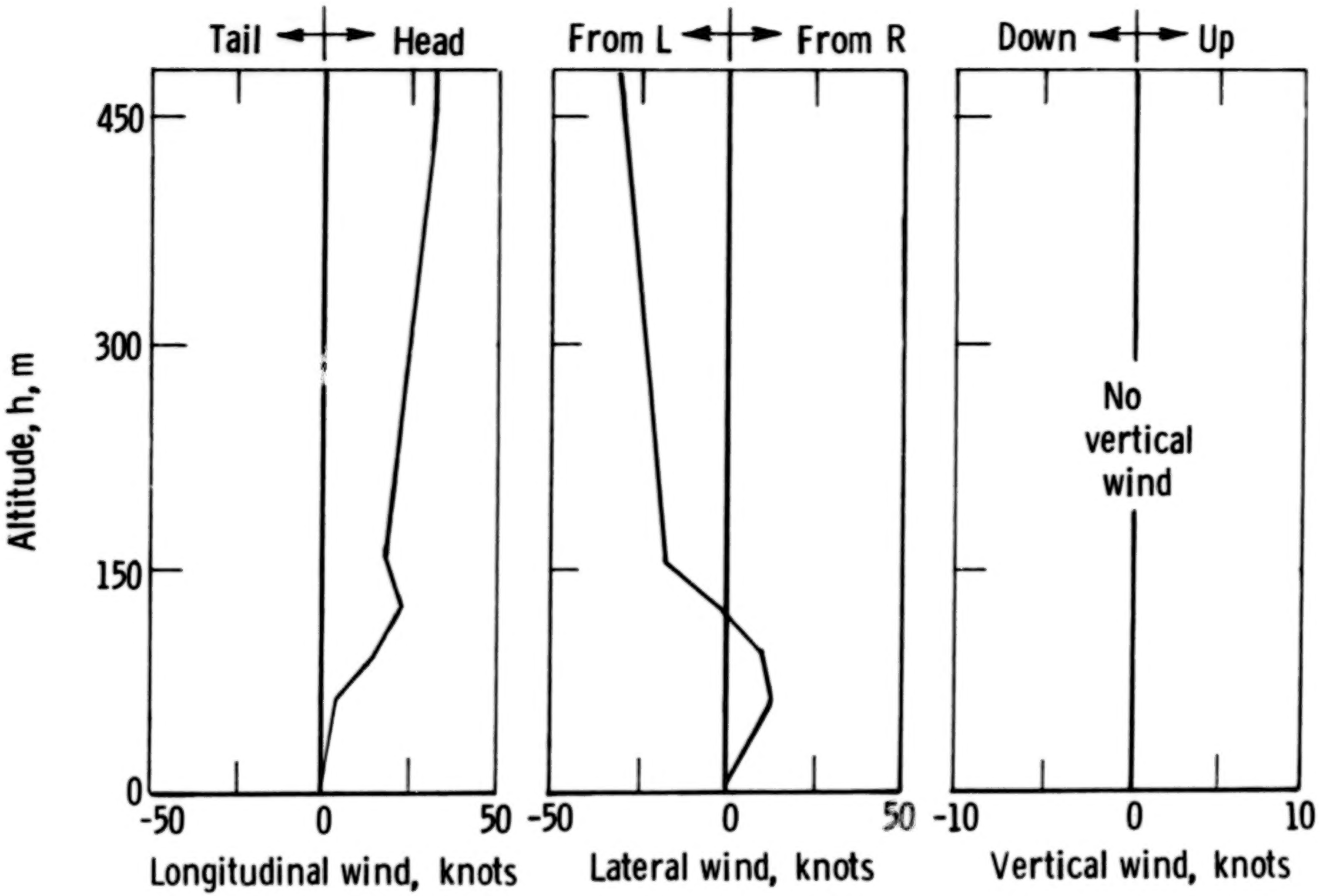

Figure 6.- Wind profile B6 (moderate severity).

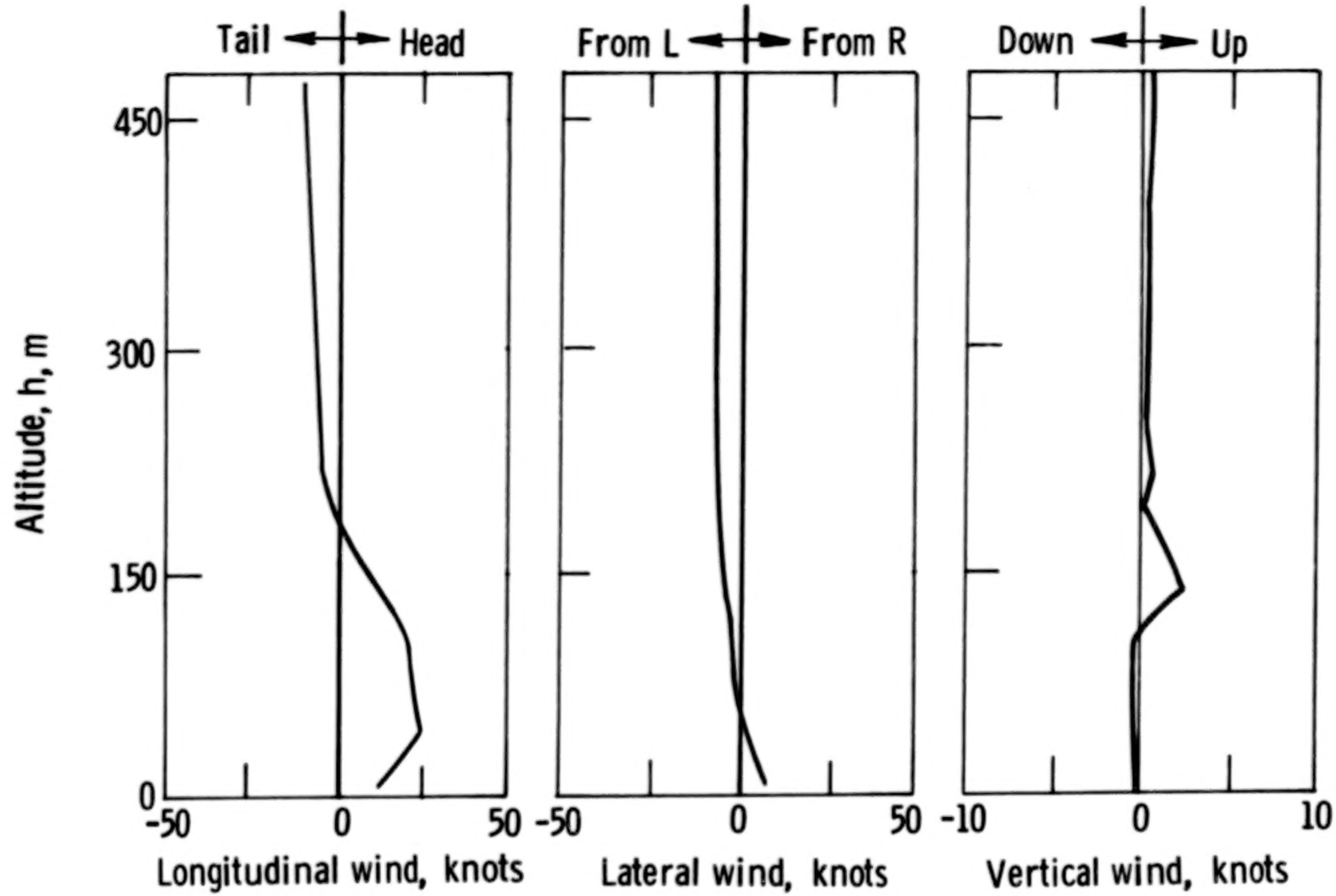

Figure 7.- Wind profile B7 (moderate severity).

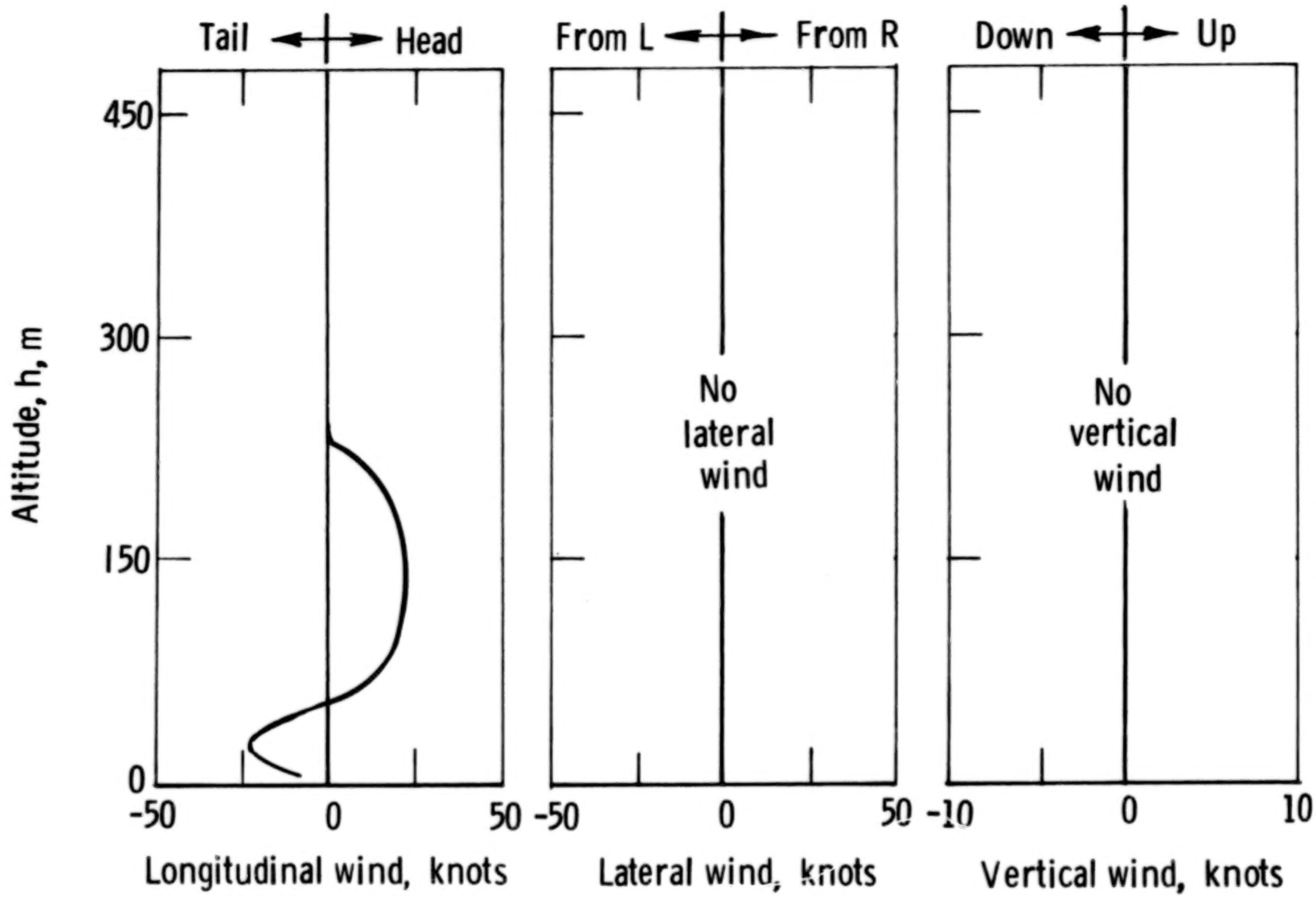

Figure 8.- Wind profile D3 (high severity).

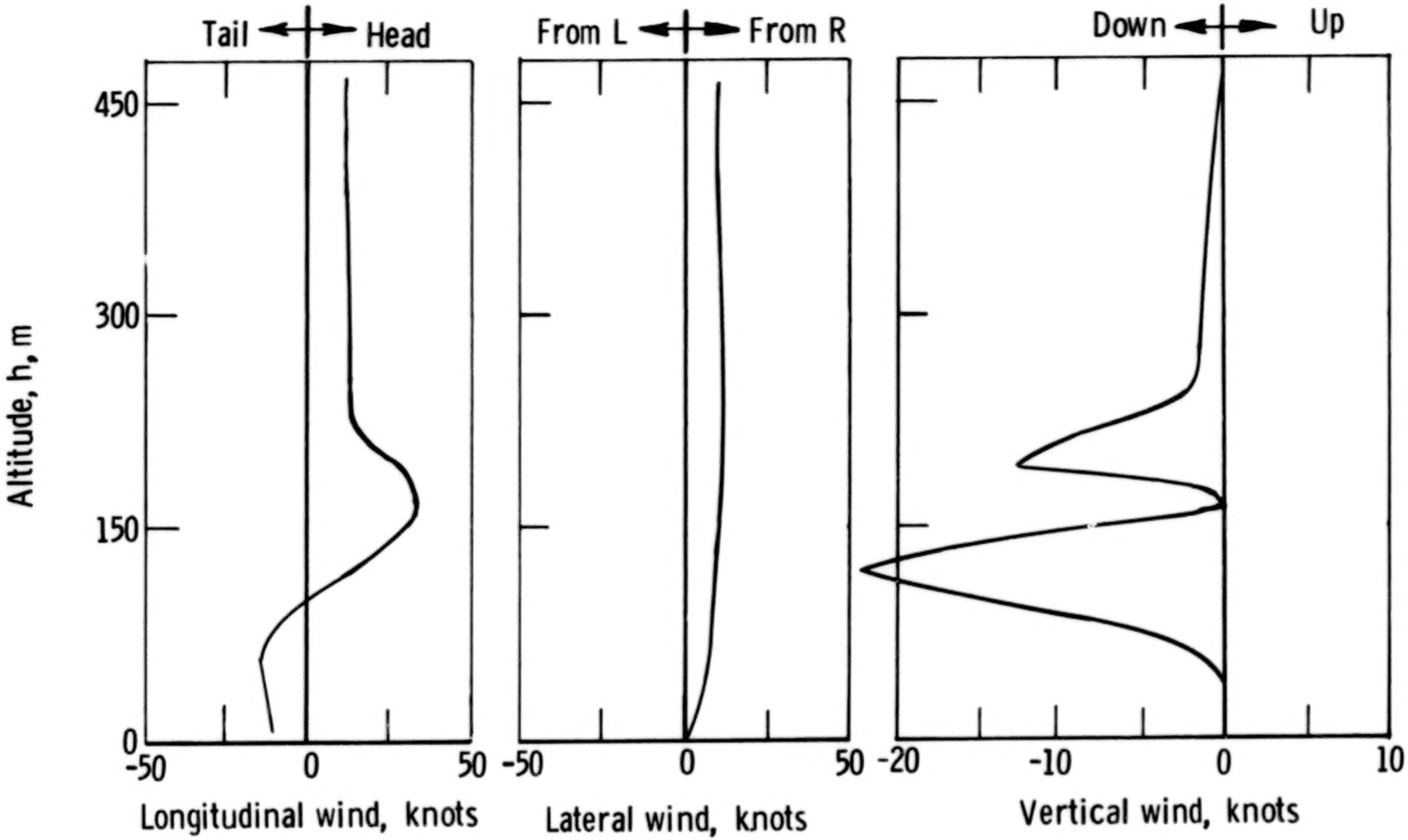

Figure 9.- Wind profile D10 (high severity). (Similar to profile at Eastern Airlines crash at John F. Kennedy International Airport.)

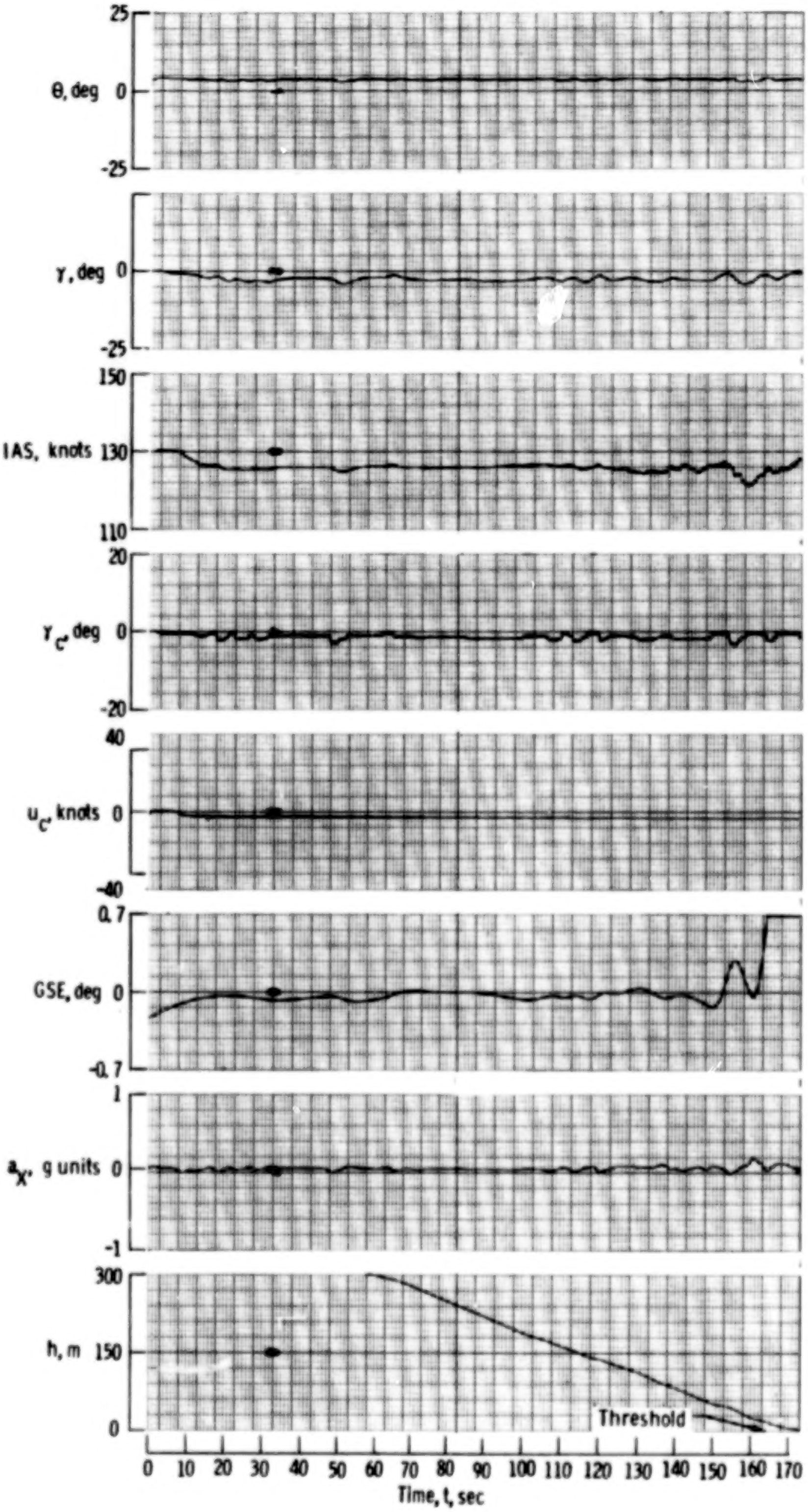

Figure 10.- Typical flight using decoupled controls in light shear.

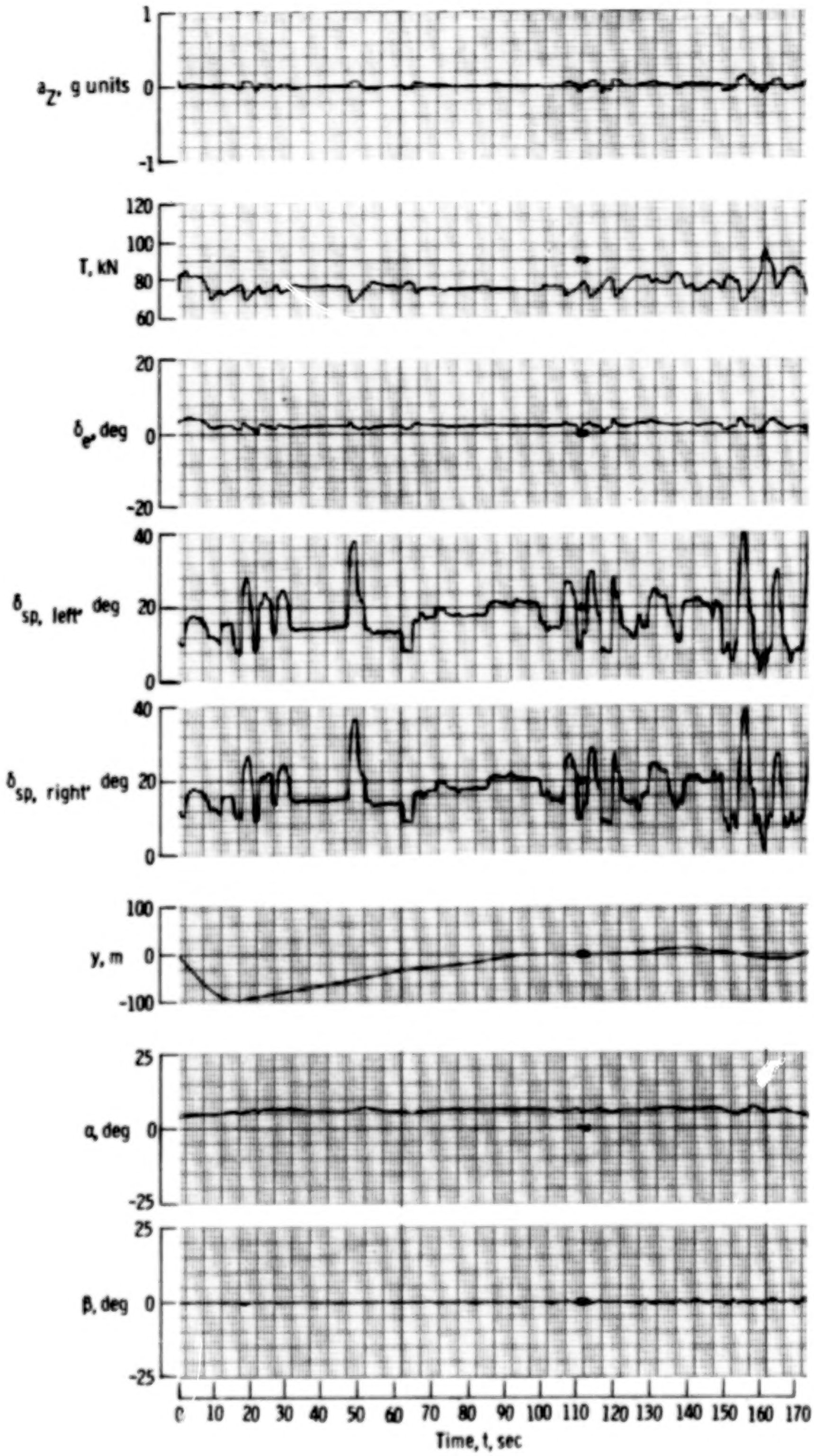

Figure 10.- Concluded.

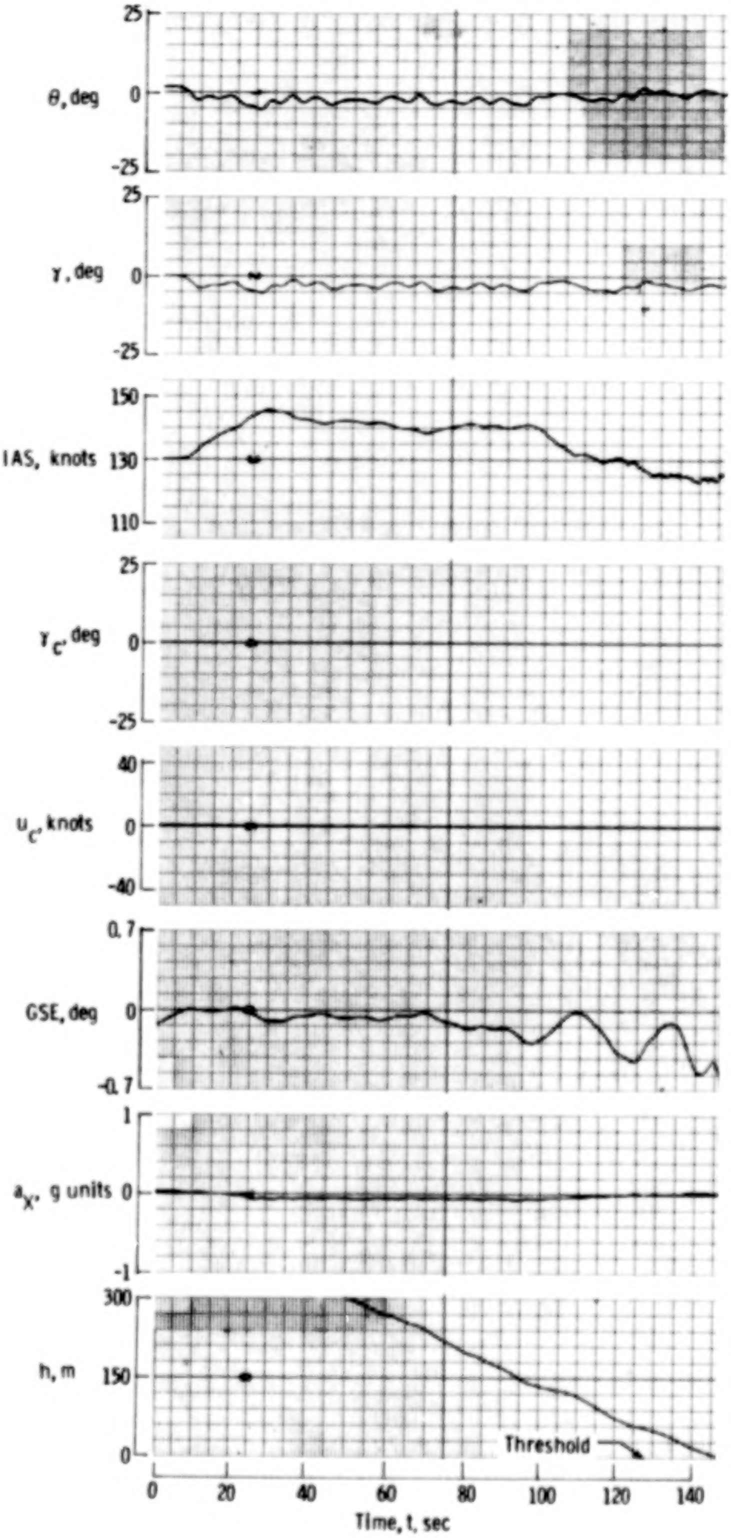

Figure 11.- Typical flight using conventional controls in light shear.

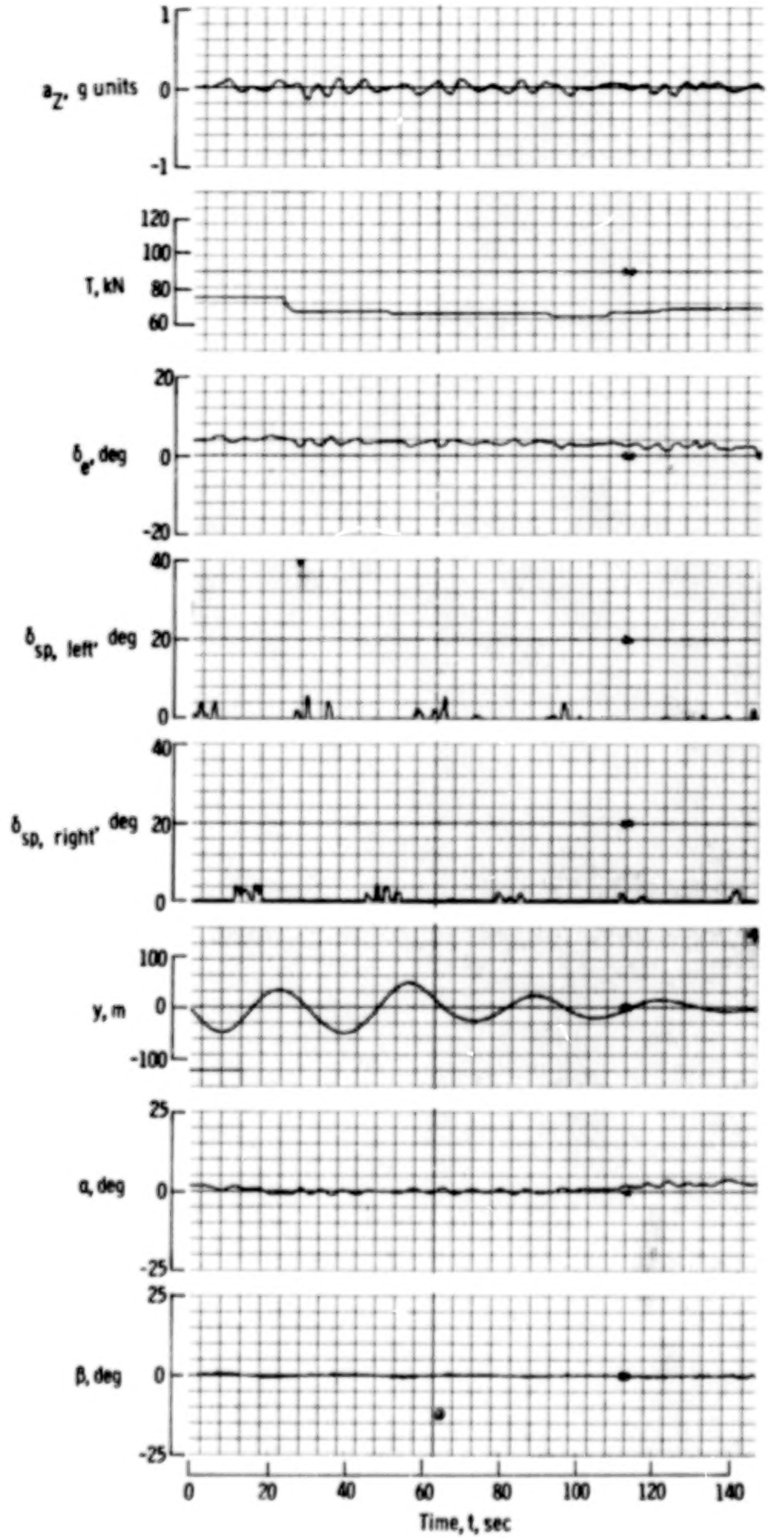

Figure 11.- Concluded.

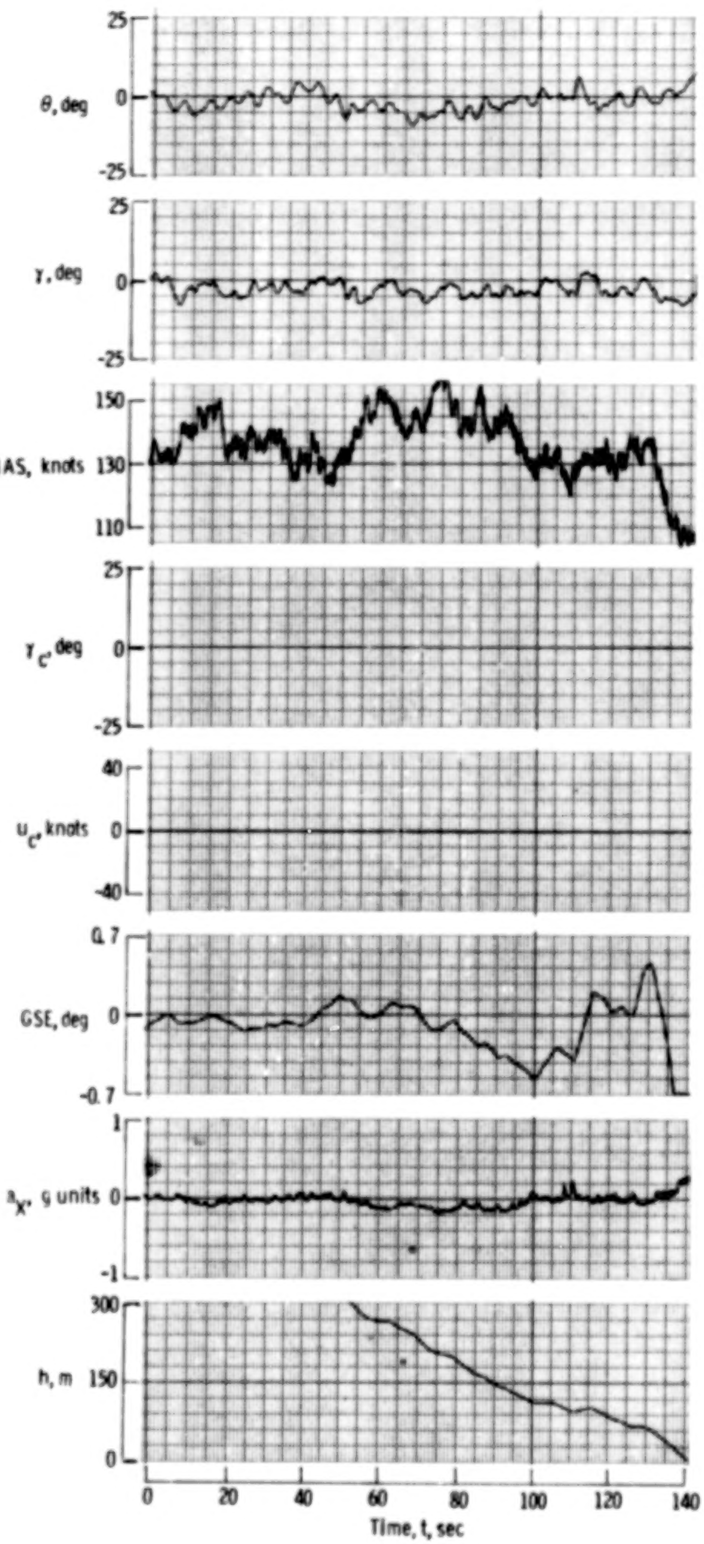

Figure 12.- Typical flight using conventionl controls in severe shear.

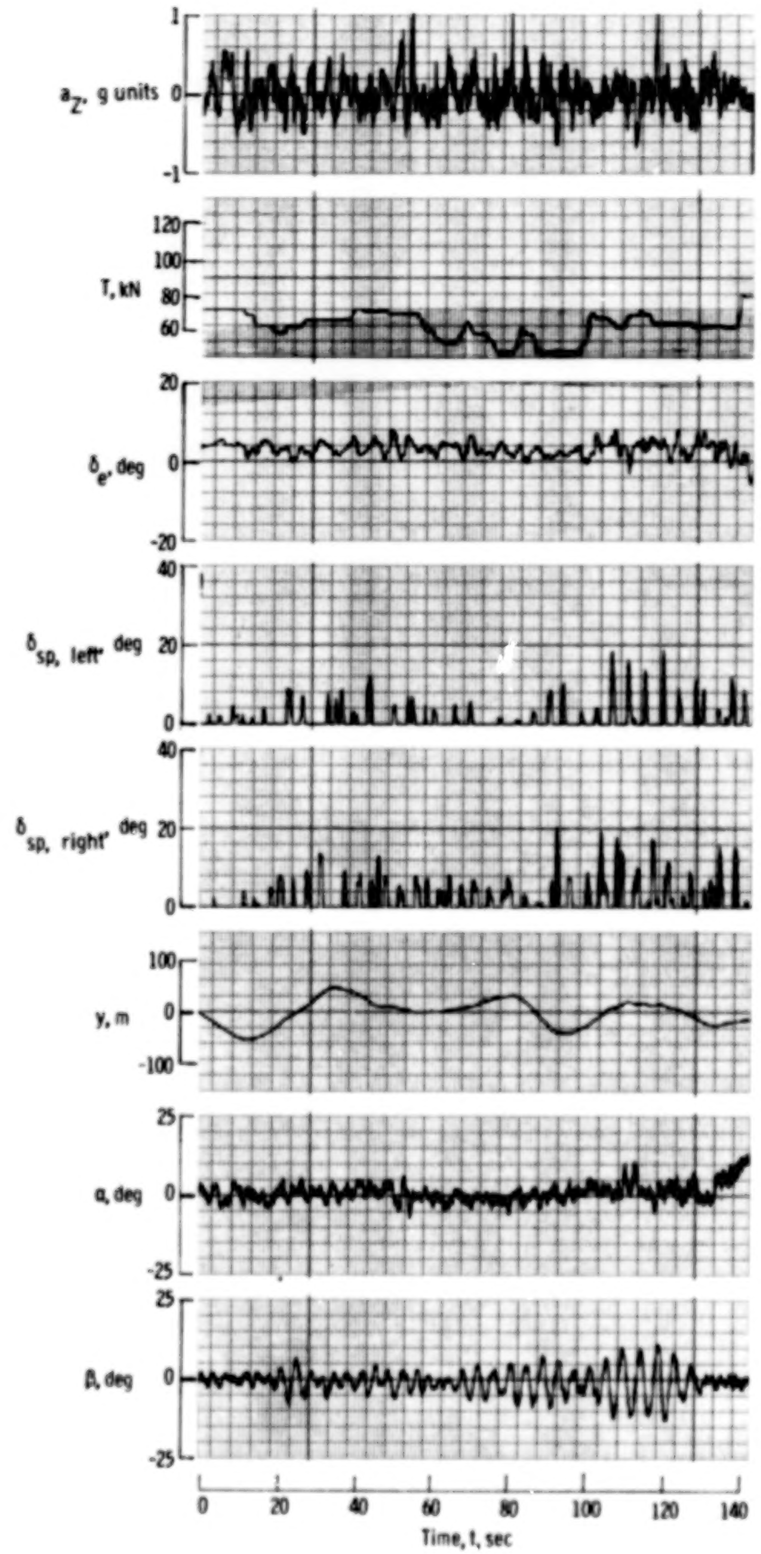

Figure 12.- Concluded.

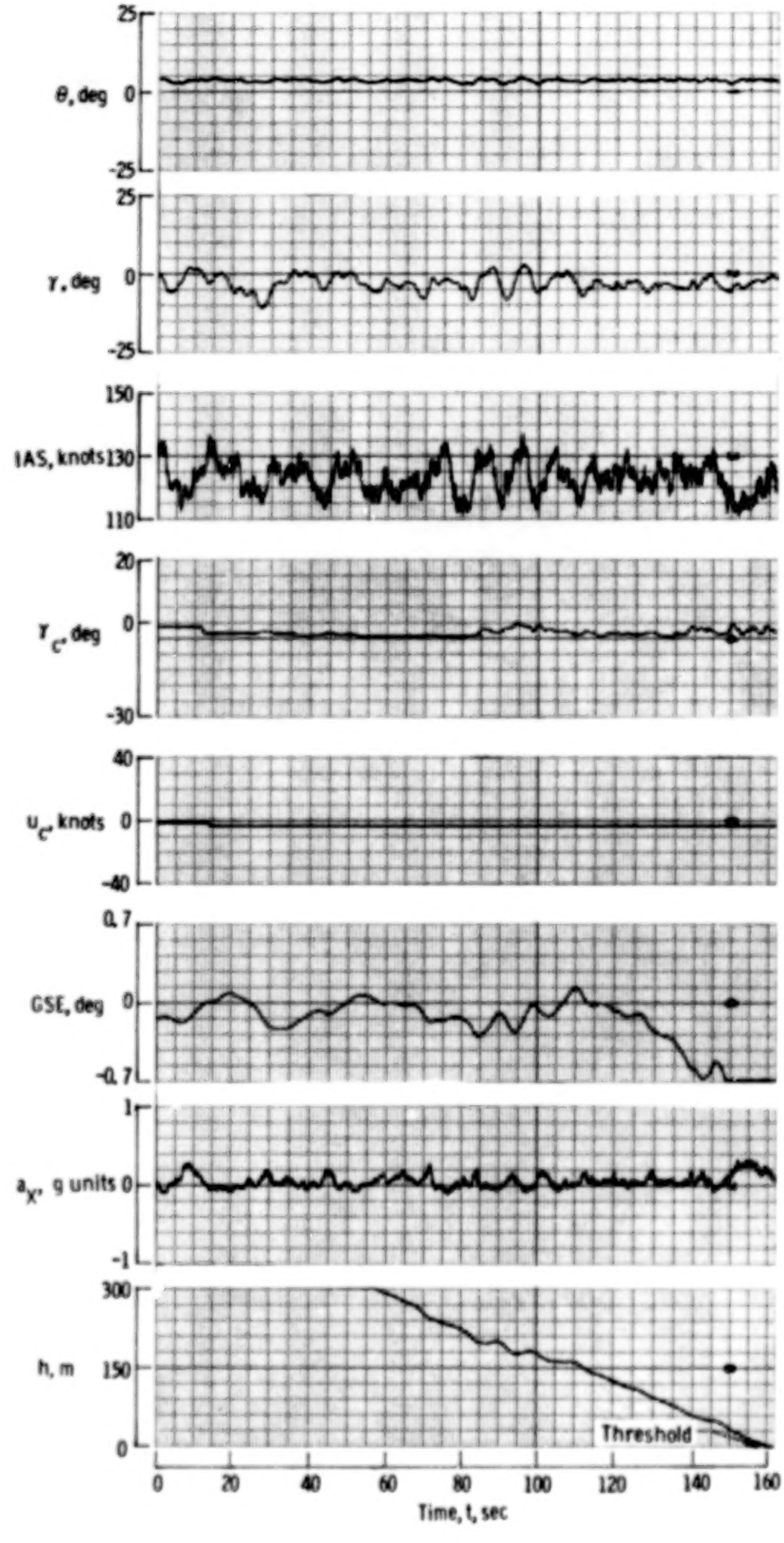

Figure 13.- Typical flight using decoupled controls in severe shear.

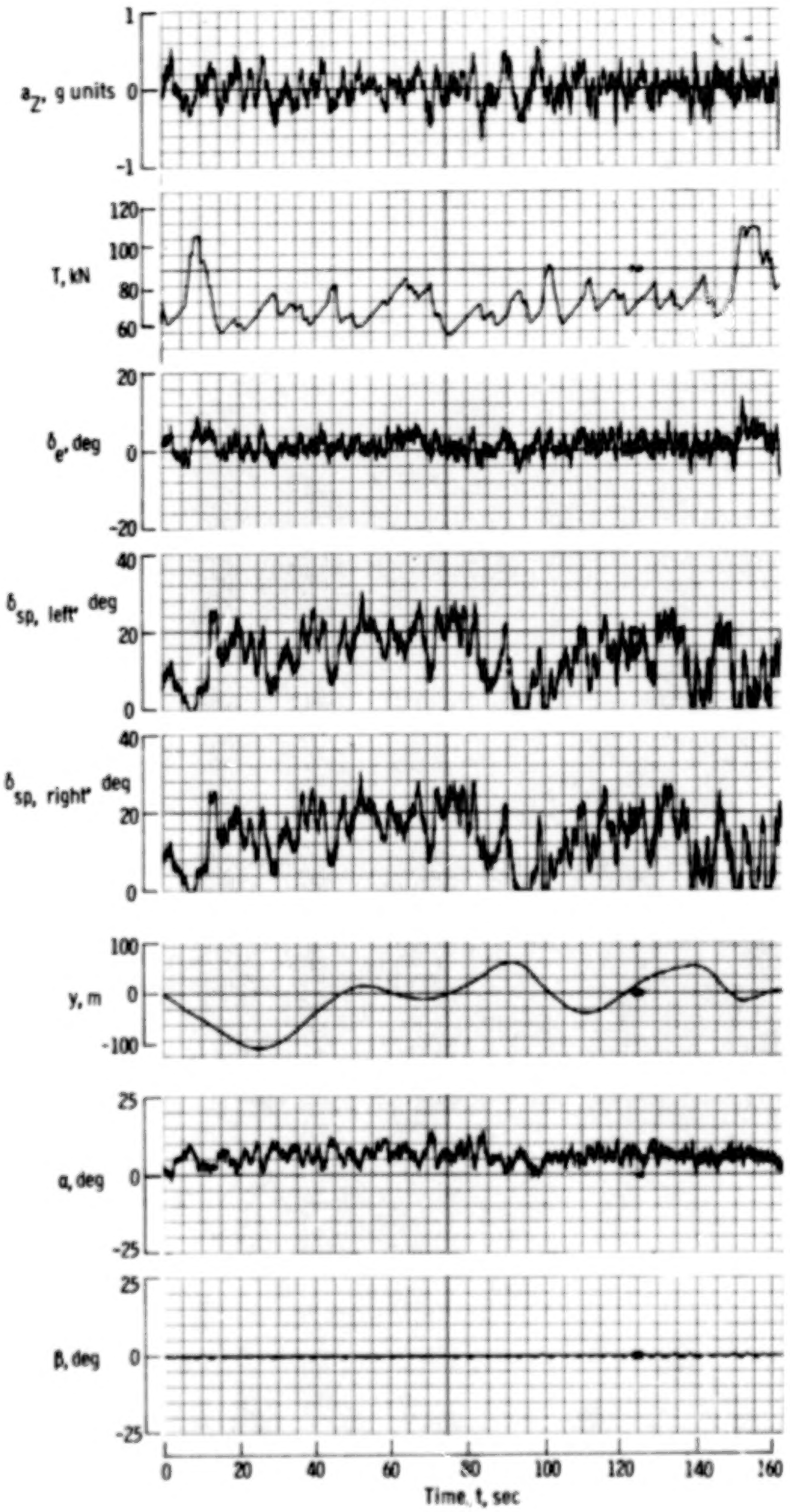

Figure 13.- Concluded.

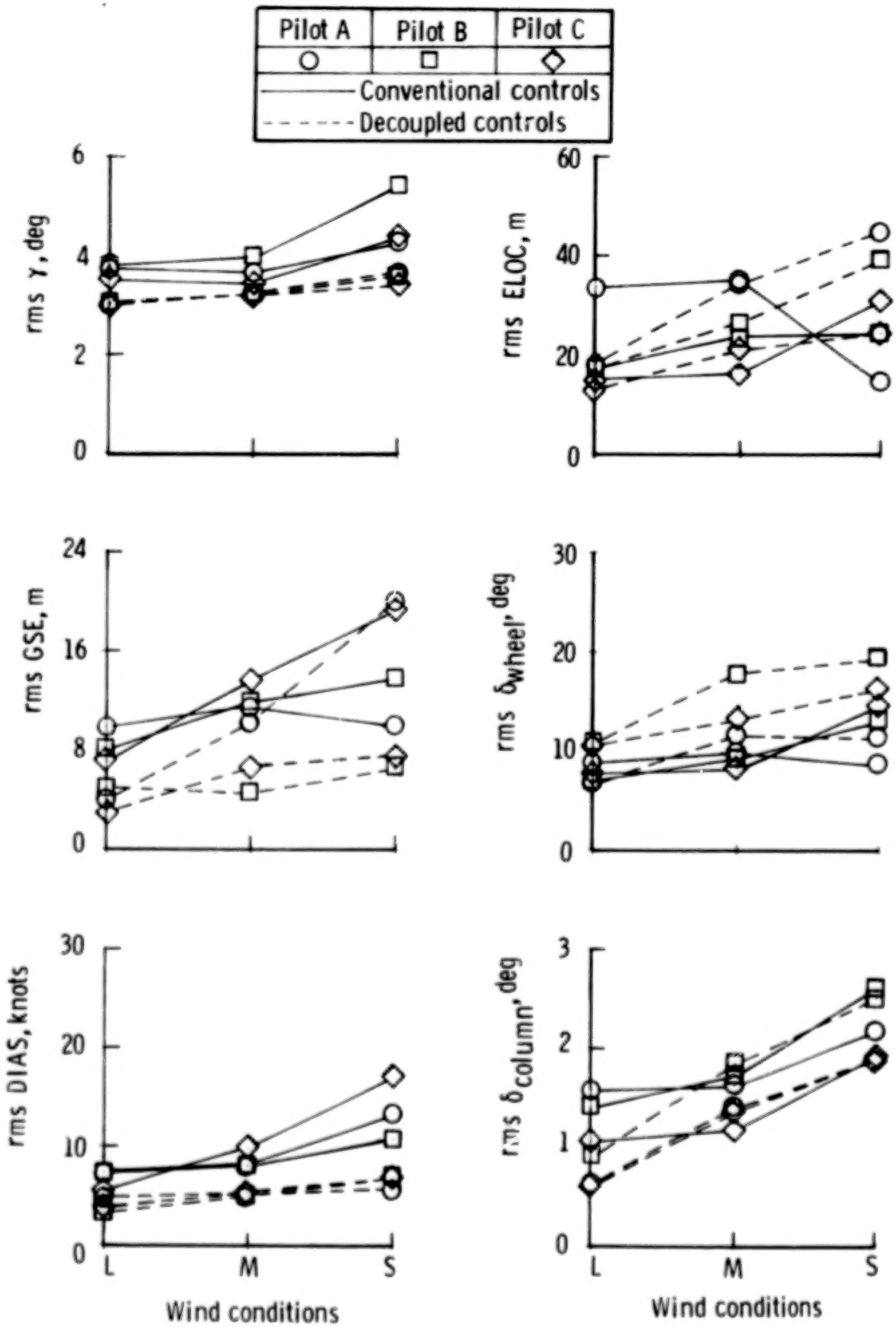

Figure 14.- Mean approach performance parameters. (L, M, and S denote light, moderate, and severe wind shears, respectively.)

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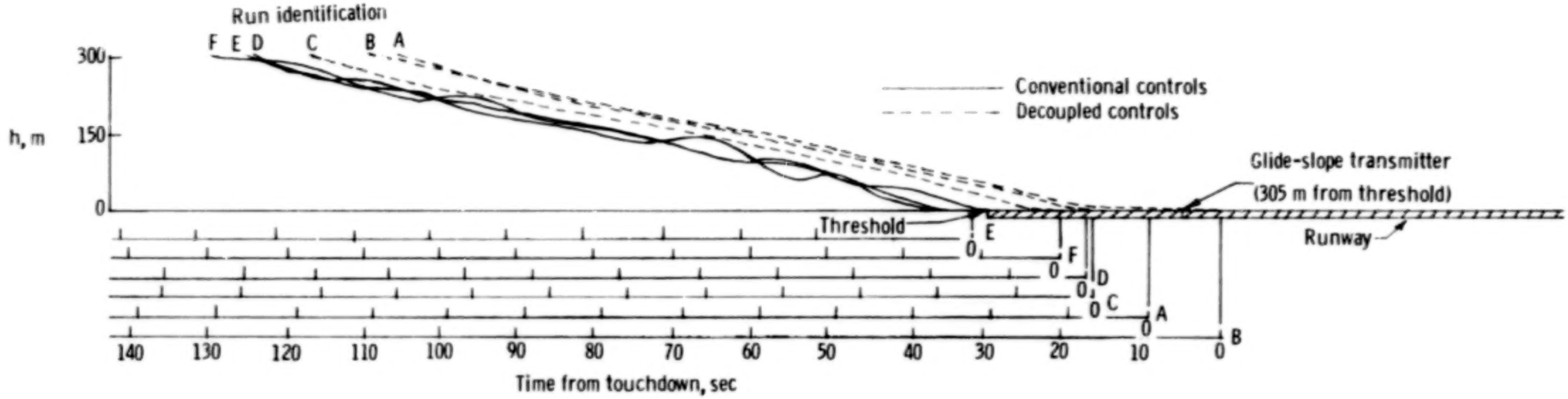
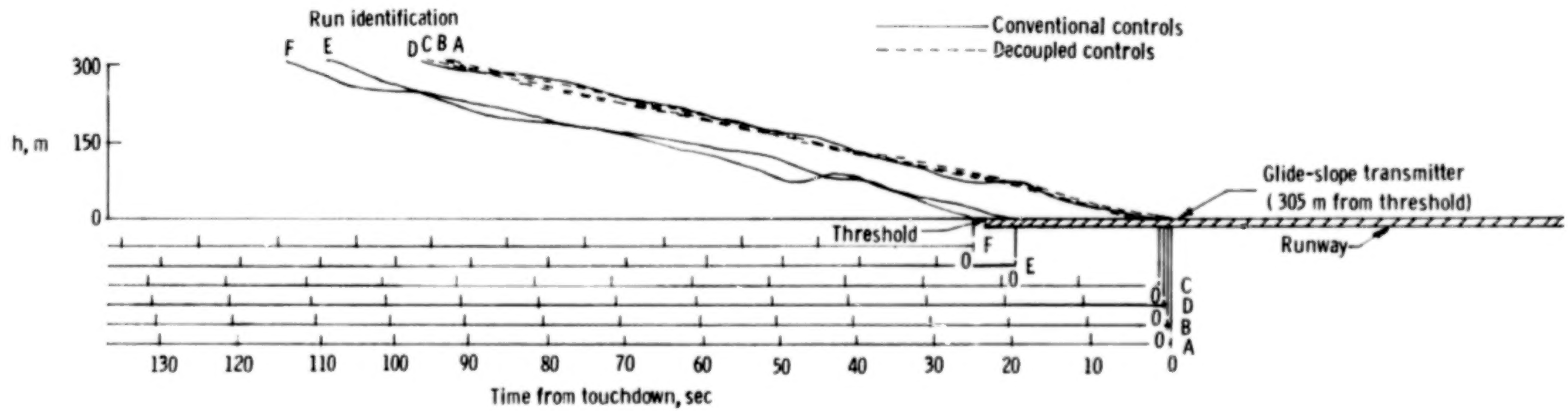
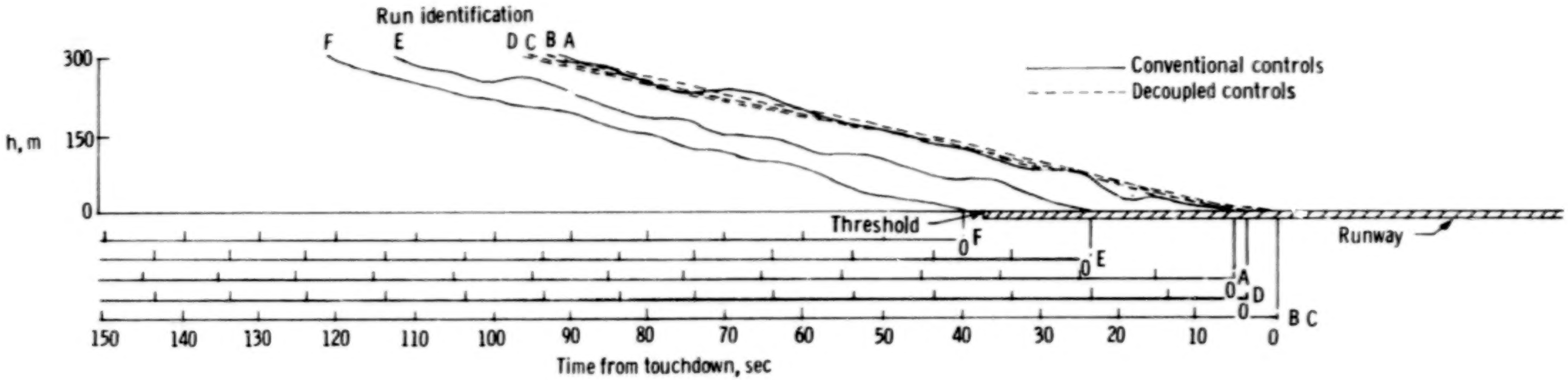


(a) Wind shear B2.

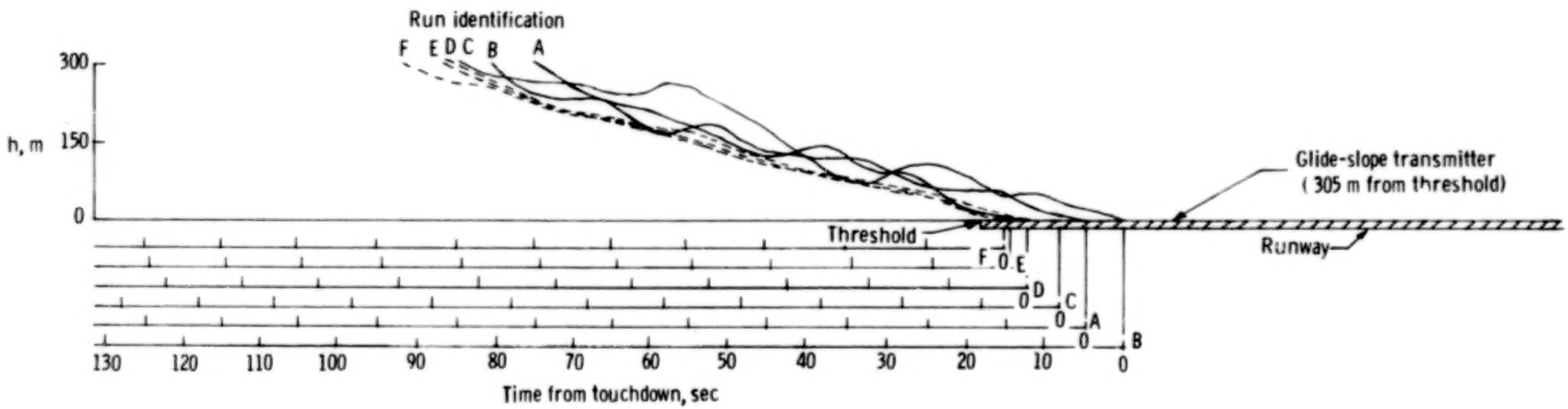


(b) Wind shear B3.

Figure 15.- Approach profiles for pilot B in light shears.

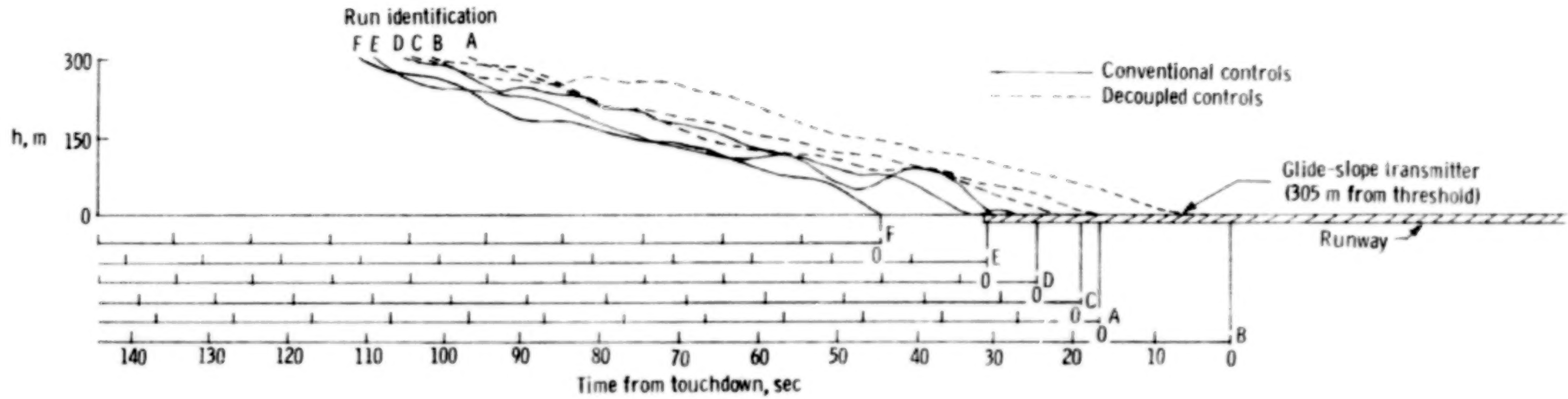


(a) Wind shear B6.

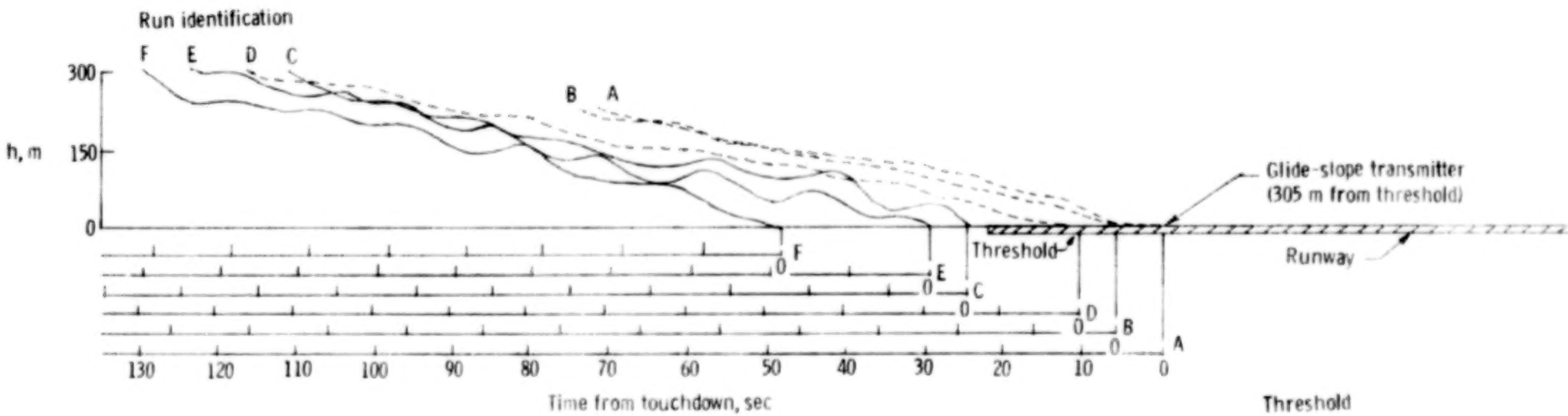


(b) Wind shear B7.

Figure 16.- Approach profiles for pilot B in moderate shears.

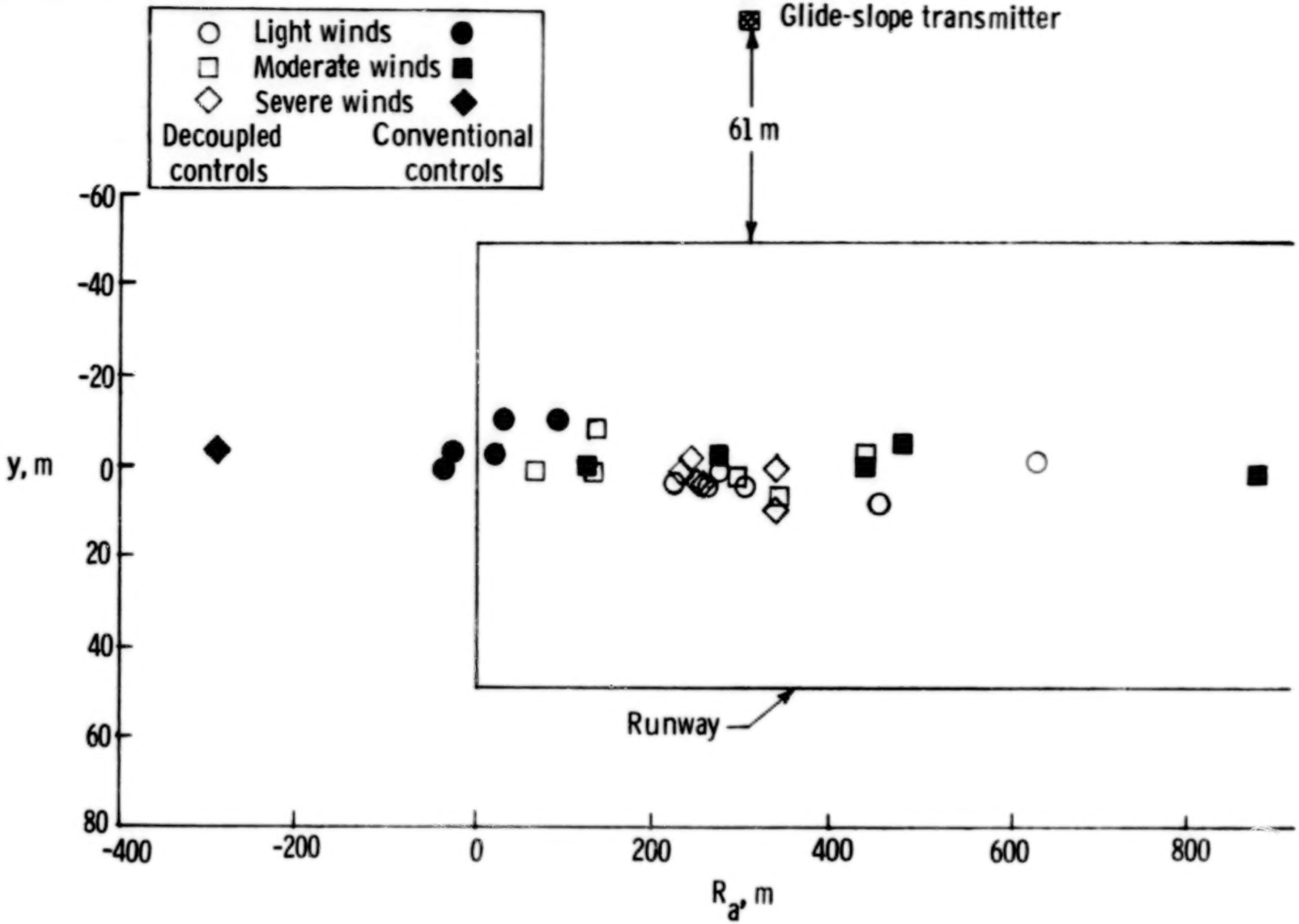


(a) Wind shear D3.



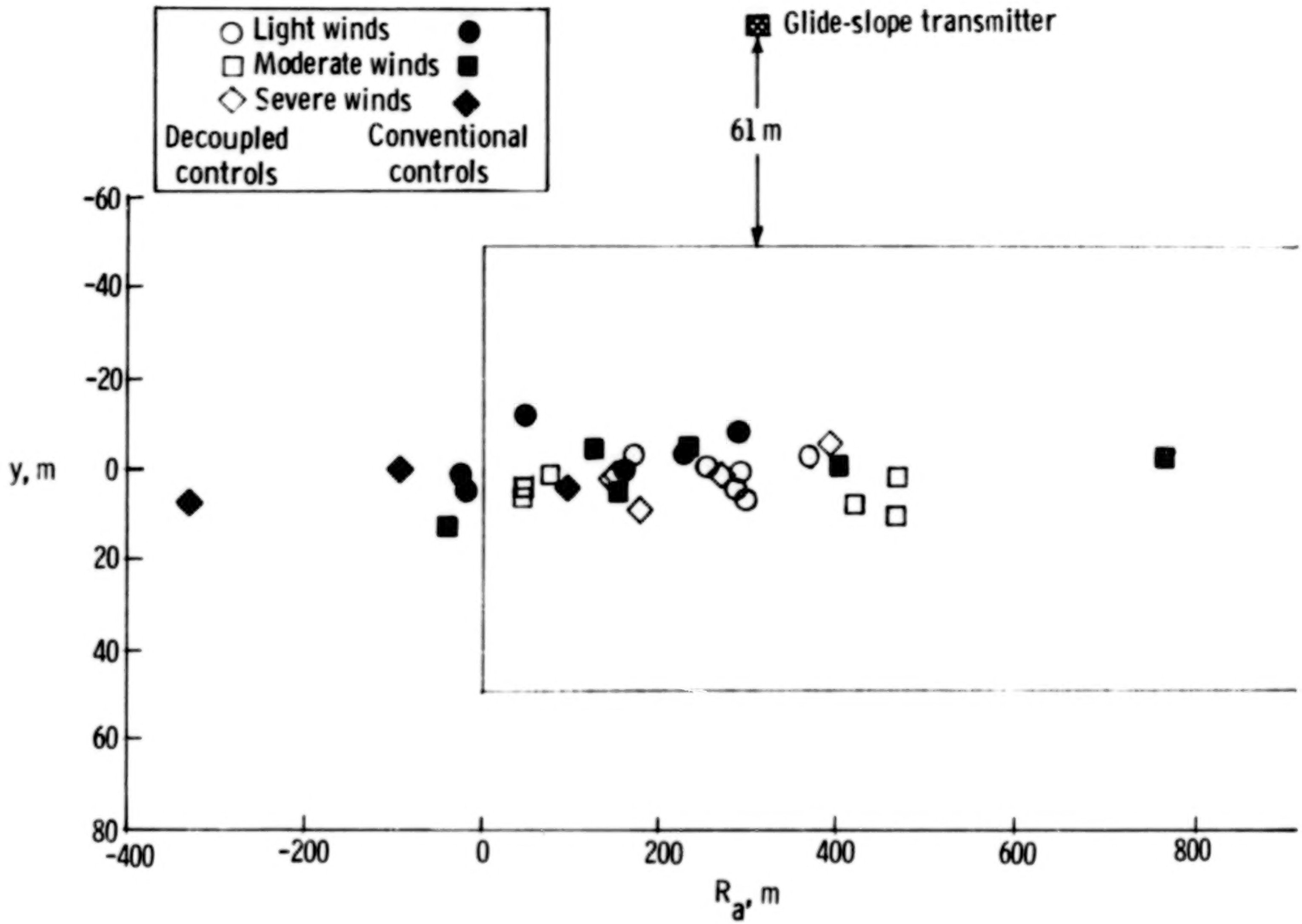
(b) Wind shear D10.

Figure 17.-Approach profiles for pilot B in severe shears.



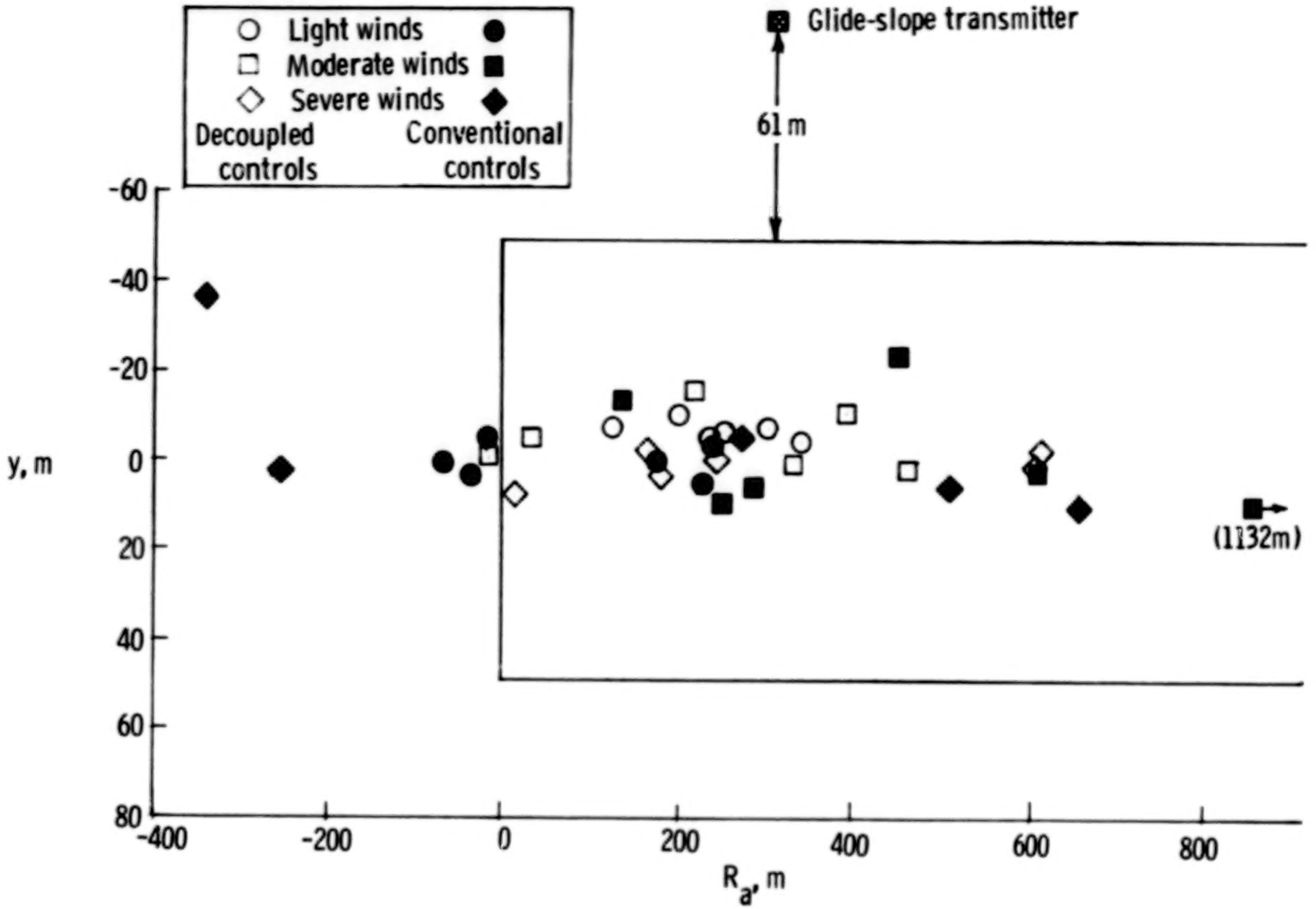
(a) Pilot A (7 runs impacted off scale using conventional controls).

Figure 18.- Touchdown points relative to runway.



(b) Pilot B (3 runs impacted off scale using conventional controls).

Figure 18.- Continued.



(c) Pilot C (1 run impacted off scale using conventional controls).

Figure 18.- Concluded.

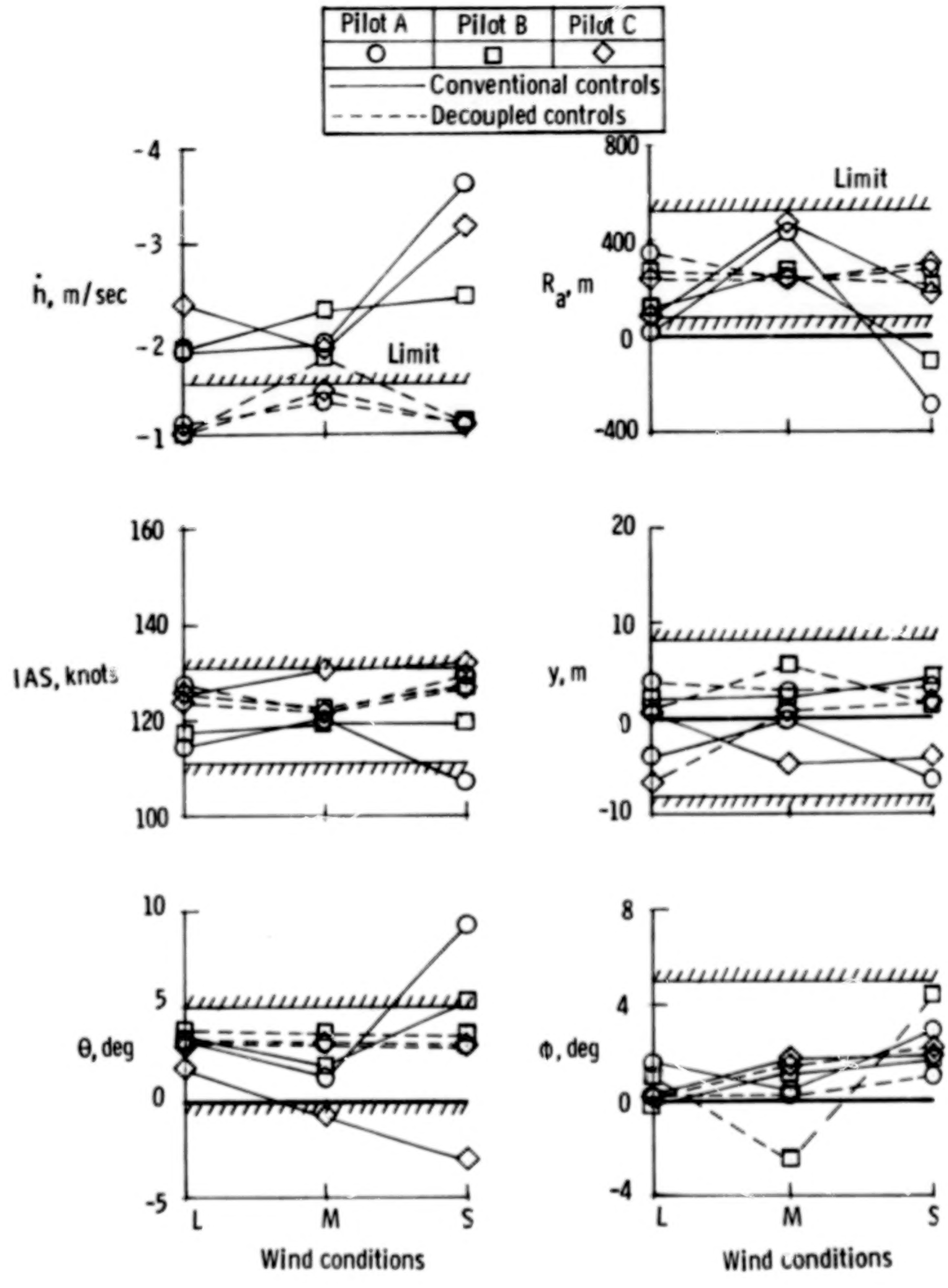


Figure 19.- Mean touchdown performance parameters. Limits are defined in reference 9. (L, M, and S denote light, moderate, and severe wind shears, respectively.)

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16. Abstract

A fixed-base simulation study has been made to evaluate the use of decoupled longitudinal controls during the approach and landing of a typical twin-engine jet transport in the presence of wind shear. The simulation included use of a localizer and flight director to capture and maintain a 3° glide slope. The pilot then completed the landing by using visual cues provided below an altitude of 200 m by closed-circuit television and a terrain model. The decoupled controls used constant prefilter and feedback gains to provide steady-state decoupling of flight-path angle, pitch angle, and forward velocity. The use of the decoupled control system improved pilot performance during the approach and at touchdown in the presence of wind shears. The pilots preferred the decoupled controls and rated the task 1 to 3 increments better on a pilot rating scale, depending on wind conditions, than was the case when conventional controls were used.

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